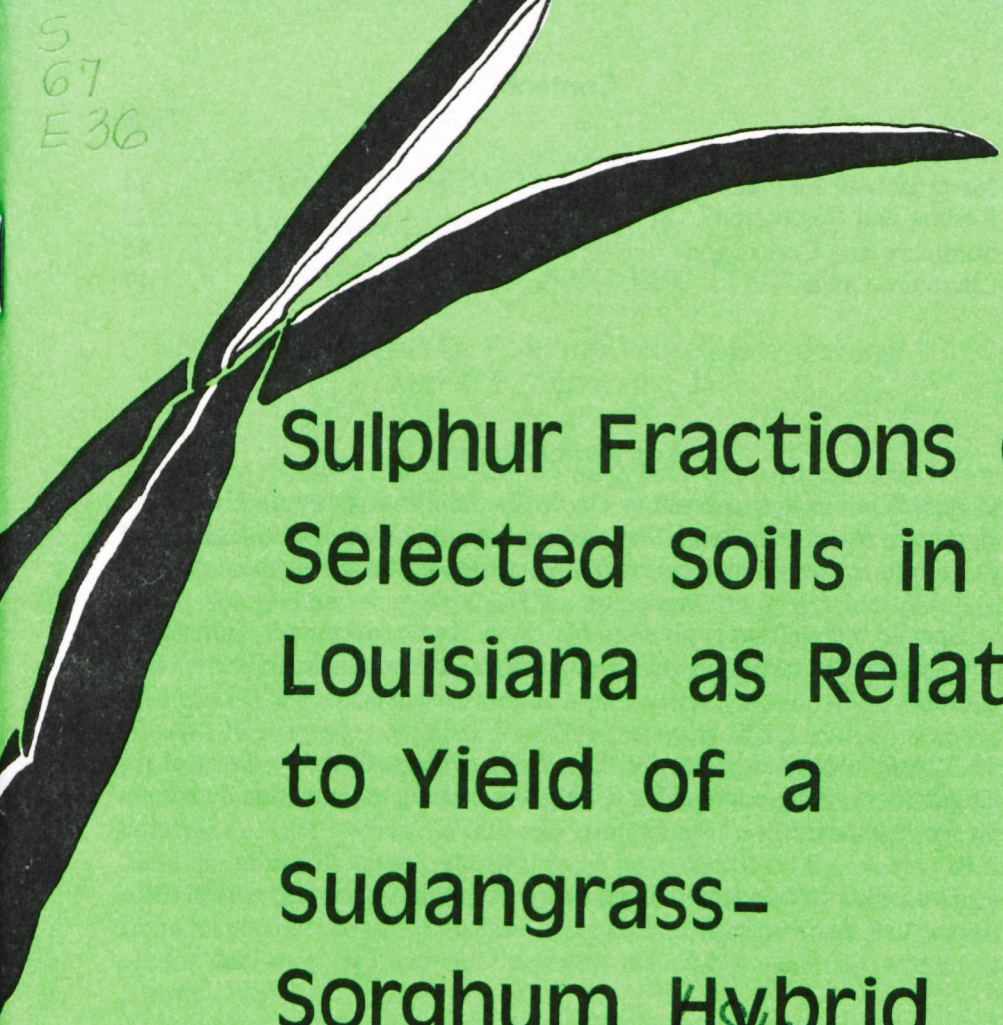
1984

Sulphur fractions of selected soils in Louisiana as related to yield of sudangrass-sorghum hybrid

William Patrick Bonner



Sulphur Fractions of Selected Soils in Louisiana as Related to Yield of a Sudangrass-Sorghum Hybrid

W.P. Bonner, D.P. Bligh,
R.H. Brupbacher, and J.E. Sedberry, Jr.

Bulletin No. 761
May 1984

LOUISIANA
AGRICULTURAL
EXPERIMENT STATION
LOUISIANA STATE UNIVERSITY AGRICULTURAL CENTER

Contents

Acknowledgments

Appreciation is expressed to Dr. P. E. Schilling, formerly Head, Department of Experimental Statistics, presently Dean of the College of Agriculture, for his assistance in the statistical analysis of the data.

Special recognition is given to Mr. S. A. Lytle, deceased, formerly of the Department of Agronomy, for classifying the soils used in the investigation.

Appreciation is expressed to Dr. W. H. Willis, formerly Head of the Department of Agronomy, for editing and making organizational changes in the manuscript.

The authors are indebted to the Freeport Sulphur Company for financial support of this research.

Louisiana Agricultural Experiment Station, Doyle Chambers, Director
Louisiana State University Agricultural Center, H. Rouse Caffey, Chancellor

Sulphur Fractions of Selected Soils in Louisiana as Related to Yield of a Sudangrass-Sorghum Hybrid

W. P. BONNER,[1] D. P. BLIGH,[2] R. H. BRUPBACHER,[2] AND J. E. SEDBERRY, JR.[2]

Sulphur (S) deficiencies recently have been appearing in the United States and many parts of the world with increasing frequency. Many of the coarse-textured soils of the southeastern United States are low in organic matter, the principal source of S for crops. Many of these soils are highly leached and may be classified as potentially S deficient (Jordan, 1964).

The principal factor contributing to the increased need and use of S fertilizers is the trend toward use of high analysis, essentially S-free fertilizers. Higher rates of other fertilizer materials and improved cultural practices have resulted in increased crop yields, which in turn have caused a corresponding increase in the S needs of crops. Restrictions on sulphur dioxide emissions into the atmosphere, and concentration of these emissions in urban industrial areas have decreased the amount of S available to crops from rainfall. Other factors responsible for the more frequent occurrence of S deficiencies are the substitution of natural gas and oil for coal as a fuel and the decreased use of S-containing pesticides, (Burns, 1967).

There is no acceptable method presently for determining the S content of soils and adequately predicting yield responses to applications of S. Most investigations have been directed toward the determination of total S, organic S, or sulphate-S (SO_4-S). Although numerous investigations have demonstrated that most of the S present in soils is associated with organic compounds, very little information is available as to the nature of the organic complex. Recent work has indicated that the organic S contents of soils can be divided into two distinct fractions: (1) organic S which is bonded directly to carbon and is reducible to inorganic sulphide with a Raney nickel catalyst (Lowe and DeLong, 1963), and (2) organic S which is not bonded directly to carbon and can be reduced to hydrogen sulphide by hydriodic acid (Freney, 1961).

[1]Formerly, Associate, Department of Agronomy, Agricultural Experiment Station, LSU Agricultural Center, Baton Rouge, La. 70803; presently, President, Delta Agronomic Services, Inc., Mer Rouge, La. 71261.

[2]Research Associate and Professors, respectively, Department of Agronomy, Agricultural Experiment Station, LSU Agricultural Center, Baton Rouge, La. 70803.

Previous investigations have indicated that the S content of certain soils in Louisiana is relatively low, and yield responses to applications of S may be obtained. Only limited data are available that show the relationship between yield responses to applications of S and the S content of these soils. The relationship of various organic fractions to the S status of major soils has not been determined in Louisiana.

This investigation was initiated with the following objectives: (1) to determine the effect of S applications on the yield and chemical composition of Funk 78F sundangrass-sorghum hybrid grown on selected surface soils and subsoils in the greenhouse; (2) to determine the extractable S content of these soils using five extracting solutions; (3) to relate the extractable S content of the soils to yield responses from applications of S; and (4) to determine the relationship among the various fractions of organic S in soils and the S status of selected soils.

Review of Literature

The value of sulphur (S) as a plant nutrient has been known since the mid-eighteenth century. Pastor Meyer of Kupferze, Switzerland observed crop stimulation from the use of gypsum in 1768. These early studies with "land plaster" caused spectacular increases in clover growth according to Alway (1940). There was some dispute among early scientists as to whether the responses to gypsum were due to S or to calcium, and it was not until 1905 that the first yield increases clearly attributed to S were carried out by Dymond, Hughes, and Jupe (1905).

S deficiencies have been appearing with increasing frequency in many parts of the world. They are known to be widespread in Australia, New Zealand, South America, North America, and also in tropical areas of Africa and Asia (Anonymous, 1967). Sulphur deficiencies in the United States have been found in arid and semi-arid regions (Hunter, 1909; Neller, 1925; Conrad, 1950) as well as in humid regions (Erdman and Bollen, 1925; Harris, et al., 1945; Bertramson, et al., 1950; Neller, et al., 1951).

A very comprehensive regional investigation to determine S supplies and requirements for crops grown under field and greenhouse conditions (Jordan, 1964) was conducted by agronomists in the southeastern region of the United States. From 1953 to 1956, uniform regional field and greenhouse experiments were initiated in eight southern states. Applications of S increased the yields of cotton, forage, and tobacco in 15 of the 21 experiments.

There has been only a limited amount of research conducted in Louisiana to determine the response of crops to S fertilization. McMichael (1949) observed a significant increase in the vegetative growth of cotton grown on Ruston loamy fine sand following an application of 300 pounds of S and 1,000 pounds of limestone per acre.

Grafton (1950) conducted a field investigation to determine the effects of S on the yield of soybeans produced for hay and seed on Ruston loamy fine sand. The use of elemental S without limestone caused a highly significant decrease in yield of soybean hay and seed. When S was used in combination with limestone, there was no depression in yield of hay, and a significant increase in yield of seed was obtained. The soil contained 0.03 percent total S and it was concluded that this amount of S was sufficient for growth and development of soybeans on Ruston soil.

Wilcox and Sedberry (1954) conducted a field investigation to determine the effects of S on yield and chemical composition of cotton plants grown on Shubuta fine sandy loam. Application of 44 pounds of S resulted in a yield increase of 273 pounds of seed cotton per acre.

Jeane (1954) investigated the relationships among S, magnesium (Mg), and phosphorus (P) in the nutrition of white clover grown on Bowie fine sandy loam. The results indicated that additions of dolomitic limestone and S gave significantly higher yields of clover than did dolomitic limestone without S. Brupbacher and Sedberry (1965) studied the effects of different sources of Mg, S, and liming materials on yield and chemical composition of clover grown on soils from the Coastal Plain areas of Louisiana. Significant increases in yield of clover grown in the greenhouse were obtained when S was used in combination with pulverized oyster shells and with dolomitic limestone. The highest yield of clover occurred on soils that received both S and Mg.

Bonner (1969) studied the effects of S on yield and chemical composition of clover grown on four surface soils and subsoils in the greenhouse. The application of S significantly increased yield of clover grown on all surface soils and three subsoils. There was no significant correlation found between S extracted from the soils with either acid ammonium acetate or sodium bicarbonate solutions and yield responses to applied S.

Golden (1972) conducted six field experiments between 1966 and 1968 to determine the effects of applied P and S on yield and chemical composition of sugarcane. Sulfur increased yield significantly in one of the six experiments. Application of 24 pounds per acre of S resulted in a yield increase of 1.67 tons of sugarcane and 570 pounds of sugar per acre.

Several diagnostic methods and techniques have been successfully employed by soil and plant scientists to determine the S status of crops and soils. One of the most reliable diagnostic methods has been evaluation of yield responses to various sources and rates of S applied in the field and in the greenhouse. Other methods which are rapid, precise, and relatively inexpensive include chemical analysis of soils and plant tissue. However, these methods must be supplemented with greenhouse

and field experiments to determine which laboratory method consistently reflects the soil-plant relationship system most accurately.

Plant analysis for diagnosing S deficiency is based on the theory that S should be present in the plant at a concentration which is sufficient for unrestricted plant growth. This concentration of S in plant tissue is commonly referred to as the critical percentage (Ulrich and Hills, 1967).

Total S, SO_4-S, and the N:S ratio have been used to detect S deficiency in plants. Total S has been the obvious choice, since it is directly related to the S supply in the soil (Ensminger and Freney, 1966).

Bledsoe and Blaser (1947) reported that S-deficient red clover contained 0.14 to 0.15 percent total S and that black medic clover contained 0.10 to 0.12 percent S when grown on soils deficient in S. Brupbacher and Sedberry (1965) found that S-deficient red clover contained an average of 0.10 percent S. Bonner (1969) presented data which indicated that the critical concentration of S in red clover was 0.13 percent.

Lancaster, et al. (1971) found that S-deficient sudangrass contained 0.05 percent S and that the application of 40 ppm of S increased the S concentration in plant tissue to 0.14 percent. Ensminger and Freney (1966) presented data indicating critical concentrations for total S in various crops. These values ranged from a low of 0.15 percent for cotton in the early bud stage to a high of 0.30 percent for a grass mixture consisting of poa, rye, and cocksfoot.

Chemical determination of SO_4-S concentration in plant tissue has proven to be a useful technique in diagnosing S deficiency. Sulphate-S concentrations in legumes have been shown to be related to the S status of soils by Spencer (1959), Walker and Bentley (1961), Jones (1962), and Jones and Martin (1964). Critical concentrations of sulphate-S for several plant species have been found to range from 100 ppm for fruit trees to 320 ppm for perennial ryegrass (Ensminger and Freney, 1966).

Several workers have attempted to relate the N:S ratio in plant tissue to S deficiency. Bardsley and Jordan (1957) found that the ratio of N:S ranged from 20:1 to 30:1 with a mean of 24:1 in S-deficient clover. Where S was applied, the N:S ratios ranged from 10:1 to 17:1 with a mean of 14:1.

Ergle and Eaton (1951) concluded that with an adequate supply of S, the N:S ratio in mature cotton leaves was 17:1. The authors reported that S became a limiting factor when the ratios were wider than 17:1. Loosi (1952) noted that feeds having a N:S ratio wider than 15:1 might be assumed to be deficient in S for ruminants.

Pumphrey and Moore (1965) found the N:S ratio in alfalfa to be relatively constant over a wide range of growth stages and suggested a ratio of 15:1 or above as indicative of S deficiency. Stewart and Whitfield (1965) concluded that S deficiency may be suspected when the N:S ratio of forage exceeds 17:1.

Data presented by Lancaster, et al. (1971) indicated that with an adequate supply of S, N:S ratio in sundangrass was 20:1 and that N:S ratios as high as 72:1 were obtained in S-deficient sudangrass. N:S ratios in orchardgrass and ryegrass receiving sufficient applications of S for maximum yields were 11:1 and 9:1, respectively.

There is very little information available concerning the nature of available S in soils. Total S content of soils indicates the reserves of this element which may be converted by chemical or biological action into sulphate-S, the form most readily available to plants (Ensminger and Freney, 1966). Total S content of soils may range from near zero to above 0.6 percent (Burns, 1967).

Nelson (1964) reported that the average total S content of 12 Mississippi surface soils was 124 ppm and ranged from 60 to 282 ppm. Grava (1971) stated that Minnesota surface soils may contain from 300 to 700 ppm of total S. Total S content of 64 surface soils investigated by Tabatabai and Bremner (1972a) ranged from 57 to 618 ppm and averaged 294 ppm. Several workers have shown that the total S content of soils is not related to the amount of S available to plants (Lobb, 1954; Bentley, et al., 1955; Williams and Steinbergs, 1964).

Organic S should be included in the evaluation of the S status of soils because it represents a potential supply of this nutrient for plant growth (Bardsley and Lancaster, 1960).

According to Alexander (1961), usually half to three-fourths of the total S present in soils is associated with organic compounds. Data published by Lowe and DeLong (1963) indicated that 33 to 70 percent of the total S content of Canadian soils investigated was accounted for in the organic fraction. Lowe (1964) later reported that organic S content of soils from the Province of Quebec accounted for 53 to 90 percent of the total S. Nelson (1964) presented data that indicated that organic S content of 12 Mississippi surface soils averaged 63 percent of the total S. Organic S content of these soils varied from 26 to 91 percent of the total S.

Numerous investigations have demonstrated the importance of organic fractions in relation to S status of soils (Eaton, 1922; Freney, et al., 1962; Harward, et al., 1962; Nelson, 1964; Fox, et al., 1964).

Bardsley and Lancaster (1960) proposed a method for determining reserve S content of soils, which was concluded to be essentially a measure of organic S. Results published by Nelson (1964) indicated that reserve S and organic S are measures of the same property. Golden (1968) found that reserve S contents of 29 surface soils in Louisiana varied from 90 to 379 ppm and averaged 180 ppm. Subsoils averaged 129 ppm of reserve S and ranged from 59 to 259 ppm.

Results of many workers have shown a close relationship between organic carbon (C), organic N, and organic S contents of soils (Freney,

1960; Williams, et al., 1960; Harward, et al., 1962; Nelson, 1964; Tabatabai and Bremner, 1972a). Freney (1960) reported that eight Australian soils investigated had an average organic C:N:S ratio of 113:10:1.2. Five soils from Scotland investigated by Williams, et al. (1960) contained an average organic C:N:S ratio of 140:10:1.4. Harward, et al. (1962) stated that the mean organic C:N:S ratio of 16 Oregon soils was 145:10:1.01. Nelson (1964) found that the average organic C:N:S ratio of 12 Mississippi soils was 126:10:1.1

Tabatabai and Bremner (1970) reported a highly significant relationship ($r = 0.87$) between organic S and organic C contents of 64 Iowa surface soils. Data presented by Harward, et al. (1962) also indicated a highly significant relationship between organic S and organic N contents of 16 Oregon surface soils ($r = 0.977$). Bardsley and Lancaster (1960) obtained a highly significant relationship ($r = 0.933$) between total N and reserve S contents of 23 Mississippi surface soils. Average total N: organic S ratio of soils investigated was 9.1:1. Freney, et al (1969) reported that average total N: organic S ratio of three Australian soils was 9.7:1.

Freney (1958) stated that many organic S compounds are produced by microorganisms; however, most of them are susceptible to decomposition and do not accumulate in soils in an uncombined form. Therefore, these compounds are not readily detected in soils. Shorey (1913) extracted trithiobenzaldehyde ($SCHC_6H_5$) from a soil sample and postulated that it was formed by reaction of hydrogen sulphide produced by bacteria with benzaldehyde derived from the decomposition of lignin.

Putman and Schmidt (1959)found traces of free cystine in ethanol extracts of a nonrhizosphere soil. Paul and Schmidt (1960) found methionine sulfoxide, cystine, and methionine in soils incubated with glucose and potatassium nitrate. Sowden (1955, 1956, 1958) and Stevenson (1956) have shown that cystine and methionine occur in soils in a combined form and that these compounds are released upon acid hydrolysis.

According to Beaton, et al. (1968) soil organic S is composed of a carbon-bonded S fraction and a noncarbon-bonded S fraction. The carbon-bonded S fraction includes all forms of organic S other than covalent sulphates and most alkyl sulphones. Arkley (1961) stated that the types of organic S linkages included in this group would be disulphides (R-S-S-R), sulphydryls (R-S-H), sulphoxides (R-$\overset{\overset{O}{|}}{S}$-R), sulphinic acids (R-$\overset{\overset{O}{|}}{S}$-OH), sulphones (R-$\overset{\overset{O}{|}}{\underset{\underset{O}{|}}{S}}$-R), and sulphonic acids (R-$\overset{\overset{O}{|}}{\underset{\underset{O}{|}}{S}}$-OH). Freney

(1958) tabulated a variety of compounds isolated from plants and microorganisms that may be found in soils. A few of the more common carbon-bonded S compounds listed were methionine, cystine, cysteine, thiamine, biotin, penicillin, coenzyme A, and glutathione.

DeLong and Lowe (1962) described a procedure for determining the carbon-bonded S content of soils. Soil samples were reacted with Raney nickel catalyst in a 150 ml digestion flask attached to the digestion-distillation apparatus, and the hydrogen sylfide released was determined according to the procedure described by Johnson and Nishita (1952).

Lowe and DeLong (1963) reported that 12 to 35 percent of total S present in selected mineral soils of Quebec was in a carbon-bonded form. Widdowson (1970) found that total S content of selected Iowa surface soils contained an average of 8 percent carbon-bonded S and that in the subsoils an average of 4 percent of total S was present as carbon-bonded S.

Lowe (1964) proposed the digestion of soil samples with a mixture of hydriodic, formic, and hypophosphorus acids in a Johnson and Nishita (1952) digestion-distillation apparatus to separate the hydriodic-acid-reducible S (HI-reducible S) fraction from soils. This fraction was assumed to consist of organic sulphates and inorganic forms of S (Lowe, 1964). Arkley (1961) listed the compounds and types of compounds which would be expected to be reduced to hydrogen sulphide with hydriodic acid. Among these compounds were inorganic sulphides and polysulphides, elemental sulphur, insoluble or slightly soluble compounds such as barium sulphate, the sulphate-containing minerals alumite and jarosite, sulphate substituted in phosphate minerals, sulphate precipitated in amorphous iron and aluminum hydrous oxides, sulphate adsorbed on the surface of soil minerals, and organic sulphur such as organic ester sulphate compounds. Organic ester sulphate-S compounds which may exist in soils are sulphated polysaccharides, phenolic sulphates, choline sulphate, and sulphated lipids (Freney, 1958).

Tabatabai and Bremner (1972b) stated that the fraction of organic S described as ester sulphate-S is believed to consist largely of S in the form of organic sulphates containing C-O-S linkages. Other types of ester sulphate-S which may occur in soils are organic sulphates containing C-N-S linkages (Freney, 1961). Tabatabai and Bremner (1972b) stated that ester sulphate-S may be calculated by subtracting inorganic S from HI-reducible S.

Freney (1961) reported that covalent sulphate groups in ester linkages can account for a significant amount of the total organic S in soils. Widdowson (1970) reported that an average of 54 percent of the total S in Iowa surface soils was HI-reducible, and an average of 72 percent of the total S in subsoils was HI-reducible. Lowe (1964) found that 44, 73, and 78 percent of the total S content of three soils from the Province of

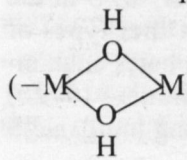
Quebec was reducible with hydriodic acid. Tabatabai and Bremner (1972b) reported that 50 percent of the total S present in 37 Iowa surface soils occurred as ester sulphate-S.

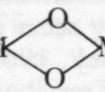
Because the nature of the available fraction of S in soil is not known, agronomists have used arbitrary methods for measuring available S. Ensminger and Freney (1966) stated that it is generally accepted that inorganic sulphate is available to plants and that S is absorbed by the plant root system largely as the sulphate ion. It has been shown that there are very small quantities of sulphate-S in the surface layer of most soils in the southeastern United States (Jordan, 1964).

Several workers have reported that many Ultisol and Oxisol soils contain appreciable amounts of adsorbed sulphate (Ensminger, 1954; Jordan and Bardsley, 1958; Kamprath, 1968). Kamprath (1968) stated that adsorbed sulphates are readily available to plants and therefore should be measured in any soil test method.

Harward and Reisenauer (1966) reported that the most important factors involved in sulphate adsorption are the type of clay minerals present, the presence of hydrous oxides, the equilibrium pH, and the equilibrium sulphate concentration. Kaolinitic clay minerals have been shown to contain more sulphate than the montmorillonite groups of clays (Ensminger, 1954; Jordan and Bardsley, 1958; Neller, 1925). Harward and Reisenauer (1966) stated that the mechanism of sulphate adsorption by kaolinitic clay minerals presumably involves an exchange of sulphate for hydroxyl in terminal octahedral coordination with aluminum. The greater retention of sulphate by kaolinite than by montmorillonite has been attributed to a higher proportion of anion exchange sites on 1:1 type clays.

Aluminum and iron oxides show a marked tendency to retain sulphate (Kamprath, et al., 1956; Berg and Thomas, 1959; Mehlich, 1964). The investigators suggested that the hydrous metal oxides tend to form coordination complexes due to the donor properties of oxygen. The complexes were reported to be polymeric compounds with various proportions of aquo $(-M-OH_2)^{+++}$, hydroxo $(-M-OH)^{++}$, ol



$(-M$ $M-)^{++++}$, and oxo $(-M$  $M-)^{++}$ groups.

Sulphate adsorption has been shown to be strongly dependent upon the equilibrium pH and the equilibrium sulphate concentration. The retention of sulphate increases as the pH decreases and as the concentration of sulphate increases (Ensminger, 1954; Kamprath, et al., 1956; Berg and Thomas, 1959; Chao, et al., 1962). Harward and Reisenauer (1966) reported that the amount of sulphate retained above a pH of 6.0 to 7.0 was not significant. The authors stated that the close relationship between pH and sulphate adsorption may be explained by the fact that as acidity is increased, the positive charge on the hydrous metal oxides also increases. Adsorbed sulphate is in kinetic equilibrium with the sulphate in solution and may be replaced by other anions of greater coordinating ability according to the series hydroxyl > phosphate sulphate = acetate > nitrate = chloride (Chang and Thomas, 1963; Chao, 1964; Bingham, et al., 1965).

Freney (1958) proposed a method for the extraction of water-soluble sulphate in soils. Spencer and Freney (1960) obtained poor correlations for the relationship between water-soluble sulphate-S and plant growth. Ensminger and Freney (1966) stated that this poor relationship was probably due to the fact that adsorbed sulphate, as well as barium and calcium sulphates, are not extracted by water, and it has been shown that these forms of sulphate are available to plants (Jordan and Bardsley, 1958; Williams and Steinbergs, 1964).

Barrow (1961) and Williams and Steinbergs (1964) used a neutral .15 percent calcium chloride solution for the extraction of sulphates in soils. These workers found that this procedure gave a good indication of available S. Widdowson (1970) reported that the S uptake by ryegrass grown on Iowa soils was highly correlated with the sulphate-S extracted with a 0.1 *M* lithium chloride solution ($r = 0.874$).

Ensminger (1954) and Fox, et al. (1964) have shown that adsorbed sulphates can be extracted with calcium or potassium phosphate solutions containing 500 ppm of P. Fox, et al. (1964) stated that calcium phosphate solution appeared to be superior to potassium phosphate solution of the same concentration because calcium ions depressed the extraction of soil organic matter, eliminating contamination due to soluble organic matter.

Spencer and Freney (1960) obtained a correlation coefficient of 0.824 between potassium-phosphate-extractable S and plant uptake of S. Fox, et al. (1964) found that sulphate-S extracted by potassium phosphate and calcium phosphate solutions containing 500 ppm of P were closely related ($r = 0.958$). Widdowson (1970) reported a highly significant correlation coefficient between calcium-phosphate-extractable S and S uptake by ryegrass.

Bardsley and Lancaster (1960) developed a method for the extraction

of soluble sulphate-S using a 0.5 *N* ammonium acetate plus 0.25 *N* acetic acid solution. These workers were unable to establish a significant relationship between extractable sulphate-S and S uptake by white clover grown on 17 Mississippi surface soils. However, S uptake by white clover was significantly related to the reserve S content of the 17 surface soils. Sanford and Lancaster (1962) obtained a significant correlation coefficient of 0.87 between acetate-soluble sulphate-S and S uptake by turnips. Jordan (1964) reported a correlation coefficient of 0.55 between acetate-soluble sulphate-S and percentage yield from 21 field experiments conducted in the southeastern United States.

Golden (1968) determined the sulphate-S content of 29 Louisiana surface soils and subsoils. The sulphate-S contents of the surface soils varied from 3.1 ppm (Commerce silt loam) to 20.4 ppm (Richland silt loam) and averaged 7.0 ppm. Sulphate-S in the subsoils averaged 9.6 ppm and varied from 2.9 ppm (Mhoon silty clay loam) to 36.2 ppm (Yahola silt loam).

A 0.5 *M* sodium bicarbonate solution adjusted to a pH of 8.5 has been suggested for extraction of S from soils by Kilmer and Nearpass (1960). Nearpass, et al. (1961) obtained a highly significant correlation coefficient of 0.89 between sodium-bicarbonate-extractable S and S "A" values obtained in a greenhouse study by an isotopic dilution method employing radioactive S. Widdowson (1970) found no significant relationship between S uptake by ryegrass and S extracted with 0.5 *M* sodium bicarbonate solution.

Ensminger and Freney (1966) tabulated the levels of extractable S in soils considered to be sufficient for plant growth. These levels were reported to be 6 to 7 ppm for ammonium-acetate-extractable S, 8 to 12 ppm for calcium-phosphate-extractable S, and 10 ppm for sodium-bicarbonate-extractable S.

Most analytical procedures for determining S are based upon the formation and measurement of insoluble sulphates. The turbidimetric procedure of Chesnin and Yien (1951) is frequently employed for determination of sulphates in soil extracts. However, colored soil extracts often interfere with this procedure. Bardsley and Lancaster (1960) successfully employed the addition of activated charcoal to decolorize the extracts. Another modification of the original procedure which has been successfully employed is the addition of an acidified "seed" solution of sulphate to initiate formation of the barium sulphate precipitate (Woodward, 1922; Thomas, et al., 1950; Steinbergs, 1955).

Several investigators have favored a method proposed by Johnson and Nishita (1952) which involves a colorimetric determination of S. In this procedure, S is reduced to hydrogen sulfide and reacted with p-aminodimethylaniline in the presence of ferric ions to form a methylene blue color.

Roe, et al. (1966) developed an indirect method for determination of sulphate using atomic absorption spectrometry to measure barium. Soil extracts or other solutions containing sulphate were added to a solution containing an excess of barium chloride. The resulting precipitate of barium sulphate was then dissolved in disodium ethylene-diamine-tetraacetic acid (EDTA), and the barium thus brought into solution was determined using an atomic absorption spectrophotometer.

Borden and McCormick (1970) also developed an indirect atomic absorption spectrometry method for determination of sulphates in aqueous solutions. Sulphates were precipitated by addition of a solution containing an excess of barium chloride, and the excess barium remaining in solution was determined using an atomic absorption spectrophotometer. Sulphate analysis by this method compared favorably with a turbidimetric and a gravimetric method.

A colorimetric procedure for determination of sulphates was described by Bertolacini and Barney (1957). Sulphates were reacted with barium chloranilate in a 50 percent ethyl alcohol solution. The intensity of the purple color developed by formation of chloranilate ion was determined colorimetrically. This method was reported to be rapid and relatively free of interference by anions such as phosphate, oxalate, bicarbonate, chlorine, and nitrate. Certain cations did interfere, but they were readily removed by ion exchange.

Heinrich, et al. (1961) reviewed a number of rapid direct titrimetric methods for determination of sulphates and concluded that, in general, these procedures tend to be inaccurate because detection of endpoints is difficult and there is serious interference.

Materials and Methods

Surface soil and subsoil samples representing 21 soil series were collected from 23 locations in Louisiana. Soils selected for investigation were representative of each of the General Soil Areas in Louisiana with exception of the Coastal Marshlands. Soil type, sampling depth, classification, and location of the soils used in the investigation are presented in Table 1. For identification purposes, each soil type was assigned a number from 1 to 23. The letters A and B were used to distinguished between surface and subsoils, respectively. Certain chemical properties of untreated soil samples are presented in Table 2.

Approximately 25-kg bulk samples of surface and subsoil were collected at each of the 23 locations. The bulk samples were air-dried to approximately 20 percent moisture, pulverized, and passed through a 6-mm sieve. A representative sample was taken from each bulk sample for chemical analysis.

Exactly 2,000 grams of soil on an oven-dried basis were placed in 3-liter plastic-lined containers. Nitrogen (N) was added to all soil samples at the rate of 224 kg per hectare. The source of N was reagent grade ammonium nitrate, NH_4NO_3, 35 percent N. Dolomitic limestone, phosphorus (P), and potassium (K) were applied to each surface and subsoil sample at the rates shown in Table 3. Soil samples were limed with dolomitic limestone which contained 42 percent $MgCO_3$ and 52.5 percent $CaCO_3$. Reagent grade monocalcium phosphate, $Ca(H_2PO_4)_2 \cdot H_2O$, containing 25 percent P was used as the source of P. The source of K was reagent grade potassium chloride, KCl, containing 52.4 percent K. Sulphur (S) treatments were applied at the rates of 0 and 56kg per hectare. Reagent grade sodium sulphate, Na_2SO_4, containing 22.5 percent S served as the source of S. Plant nutrient elements and limestone were thoroughly incorporated with soil in each container by mixing. A split-plot experiment with soils used as main plots and S treatments used as subplots was arranged in a randomized block design with three replications.

Approximately 25 Funk 78F sudangrass-sorghum hybrid seeds were placed in each container on October 13, 1970. Distilled water was used to maintain soils at approximately 70 percent of field capacity. Plants were grown for 87 days. Forage was harvested at a height of 4 cm three times during the growth period. After each harvest, the soil in each container received an additional application of N at the rate of 244 kg per hectare. Plant material harvested from each container was placed in a paper bag and dried in a convection oven at 70C for 24 hours. After drying, samples were removed from the oven and allowed to cool, and the weight of plant material was recorded in grams per container.

Table 1.—Soil type, sampling depth, subgroup, and location of soil samples used in greenhouse and laboratory investigations

Sample number	Soil type[1]	Sampling depth (cm)	Subgroup	Location (parish)
		Soils of the Mississippi River Alluvial Area		
1 A[2]	Commerce sil	0-18	Fluventic Haplaquepts	East Baton Rouge
1 B[2]	sicl	18-36		
2 A	Mhoon sicl	0-15	Fluventic Haplaquepts	Plaquemines
2 B	sic	15-30		
3 A	Sharkey c	0-15	Vertic Haplaquepts	East Baton Rouge
3 B	c	15-30		
		Soils of the Ouachita River Alluvial Area		
4 A	Gallion 1	0-15	Typic Hapludalfs	Caldwell
4 B	scl	15-33		
5 A	Gallion vfsl	0-20	Typic Hapludalfs	Richland
5 B	scl	20-36		
6 A	Hebert sil	0-15	Aeric Ochraqualfs	Morehouse
6 B	sicl	15-28		
		Soils of the Red River Alluvial Area		
7 A	Norwood sil	0.20	Typic Udifluvents	Rapides
7 B	sil	20-38		
8 A	Yahola sil	0-18	Typic Ustifluvents	Bossier
8 B	sil	18-36		
		Soils of the Coastal Plain and Flatwoods Areas		
9 A	Bowie fsl	0-13	Plinthic Paleudults	Vernon
9 B	scl	13-25		
10 A	Gilead ls	0-15	Typic Fragiudults	Lincoln
10 B	ls	15-28		
11 A	Ruston fsl	0-10	Typic Paleudults	Washington
11 B	sc	10-25		
12 A	Acadia sil	0-13	Aeric Ochraqualfs	Acadia
12 B	sicl	13-25		
13 A	Stough fsl	0-15	Aquic Fragiudults	St. Tammany
13 B	cl	15-30		
		Soils of the Coastal Prairies Areas		
14 A	Crowley sil	0-13	Typic Albaqualfs	Acadia
14 B	sicl	13-30		
15 A	Crowley sil	0-15	Typic Albaqualfs	St. Landry
15 B	sicl	15-28		
16 A	Midland sil	0-15	Vertic Ochraqualfs	Acadia
16 B	sicl	15-30		
17 A	Morey sil	0-18	Typic Argiaquolls	Acadia
17 B	sicl	18-30		

(Continued)

Table 1.—(Continued)

Sample number	Soil type[1]	Sampling depth (cm)	Subgroup	Location (parish)
		Soils of the Mississippi River Alluvial Area		
18 A	Jeanerette sil	0-13	Typic Argiaquolls	Acadia
18 B	sicl	13-28		
19 A	Loring sil	0-15	Typic Fragiudalfs	East Baton Rouge
19 B	sicl	15-30		
20 A	Memphis sil	0-20	Typic Hapludalfs	East Baton Rouge
20 B	sicl	20-36		
21 A	Olivier sil	0-18	Aquic Fragiudalfs	Franklin
21 B	sicl	18-33		
22 A	Patoutville sil	0-15	Aeric Ochraqualfs	Acadia
22 B	sicl	15-28		
23 A	Providence sil	0-13	Typic Fragiudalfs	Washington
23 B	sicl	13-30		

[1]Soils classified by S. A. Lytle, Associate Professor, Louisiana Agricultural Experiment Station.
[2]A and B represent surface soils and subsoils, respectively.

The plant material from each harvest was ground in a stainless steel Wiley mill to pass a 20-mesh screen and placed in 4-ounce specimen bottles for storage. The samples of plant material were dried in a convection oven at 70C for 12 hours to remove excess moisture prior to weighing for chemical analysis.

Concentration of N, S, P, and Mg in the plant material was determined and reported as percent on a dry-weight basis. Plant tissue samples were wet ashed using a 2:1 mixture of concentrated nitric and perchloric acids according to the procedure described by Toth, et al. (1948). The residue resulting from the digestion was filtered through Whatman No. 1 filter paper, and the filtrate was diluted to a volume of 100-ml. Aliquots of the filtrate were used for the determination of S, P, and Mg. The plant tissue was analyzed for S by a turbidimetric procedure described by Sanford and Lancaster (1962). Phosphorus was determined by the vanadomolybdate method described by Jackson (1958). A Perkin-Elmer Model 303 Atomic Absorption Spectrometer was used for determination of Mg. The total N content of the plant tissue was determined by the Kjeldahl method developed in 1883 and modified by Meeker and Wagner (1933) and described by Wright (1939). The N:S ratio of the plant tissue was calculated by dividing the concentration of N in the plant tissue by the concentration of S in the plant tissue.

Each soil sample was air-dried and ground in a Bico Type UA pulverizer and passed through a No. 20 U.S. Standard stainless steel sieve prior to chemical analysis. The dilute-acid-extractable P, K, Ca, and Mg

Table 2.—Certain chemical properties of soil samples used in the greenhouse and laboratory investigations

Sample number	Soil type	Extractable nutrients				pH	CEC pH 7.0	Base saturation
		P	K	Ca	Mg			
		ppm					me/100g	%
Soils of the Mississippi River Alluvial Area								
1 A[1]	Commerce sil	159	114	1106	319	6.1	10.1	77.4
1 B[1]	sicl	97	123	1692	538	6.7	16.2	72.8
2 A	Mhoon sicl	375	225	2100	770	6.4	26.2	54.5
2 B	sic	162	126	1760	639	7.0	15.7	61.8
3 A	Sharkey c	266	362	3140	959	6.5	30.8	64.2
3 B	c	243	262	3550	1029	7.4	28.1	69.0
Soils of the Ouachita River Alluvial Area								
4 A	Gallion 1	156	129	260	98	4.7	5.4	43.7
4 B	scl	122	127	542	356	4.7	14.5	39.4
5 A	Gallion vfsl	124	134	314	130	5.7	4.7	64.8
5 B	scl	94	73	348	131	5.7	4.9	59.3
6 A	Hebert vfsl	99	122	524	149	6.3	4.2	71.7
6 B	sicl	98	65	396	85	5.5	4.8	64.1
Soils of the Red River Alluvial Area								
7 A	Norwood sil	198	170	10,730	2143	7.5	8.8	100.0
7 B	sil	137	89	10,370	2359	7.8	7.0	100.0
8 A	Yahola sil	152	143	742	425	7.2	4.5	100.0
8 B	sil	127	94	1790	686	7.7	4.8	100.0
Soils of the Coastal Plain and Flatwoods Areas								
9 A	Bowie fsl	9	53	88	48	4.8	5.4	59.8
9 B	scl	10	34	62	58	4.9	4.4	28.8
10 A	Gilead ls	11	48	44	9	5.2	3.2	33.3
10 B	ls	9	42	40	8	5.4	1.2	42.2
11 A	Ruston fsl	18	70	256	154	6.1	6.2	53.2
11 B	sc	5	50	136	245	5.2	11.7	29.8
12 A	Acadia sil	20	167	344	130	5.6	6.8	42.7
12 B	sicl	6	98	44	134	4.7	11.3	20.7
13 A	Stough fsl	6	25	26	6	4.2	7.3	12.8
13 B	cl	4	20	16	9	4.4	4.3	23.7
Soils of the Coastal Prairies Area								
14 A	Crowley sil	34	74	1024	318	6.4	9.3	74.1
14 B	sicl	6	54	566	300	7.4	8.9	66.8
15 A	Crowley sil	46	95	686	185	5.9	8.5	48.4
15 B	sicl	9	50	718	226	7.0	8.6	54.3
16 A	Midland sil	69	82	1116	318	6.1	12.7	50.3
16 B	sicl	39	61	704	312	5.4	14.0	37.8
17 A	Morey sil	56	82	1028	170	6.2	8.2	59.4
17 B	sicl	9	57	1454	321	6.7	11.2	67.1

(Continued)

Table 2.—(Continued)

Sample number	Soil type	Extractable nutrients P	K	Ca	Mg	pH	CEC pH 7.0	Base saturation
		ppm					me/100g	%
Soils of the Mississippi Terraces and Loessial Hills Areas								
18 A	Jeanerette sil	11	89	1338	300	5.5	13.3	48.3
18 B	sicl	9	107	2290	509	6.1	18.8	62.8
19 A	Loring sil	30	93	338	102	5.7	7.8	34.2
19 B	sicl	18	70	106	174	4.9	12.1	19.2
20 A	Memphis sil	142	85	306	61	5.6	5.2	38.9
20 B	sicl	164	142	954	236	4.9	17.1	30.8
21 A	Olivier sil	97	205	194	104	5.2	7.6	38.8
21 B	sicl	68	138	142	165	4.8	9.9	33.1
22 A	Patoutville sil	20	75	310	106	4.9	5.4	40.4
22 B	sicl	7	149	1136	572	5.6	19.2	54.3
23 A	Providence sil	10	64	1072	288	6.8	8.2	82.1
23 B	sicl	3	39	130	79	5.1	9.8	14.9

[1]A and B represent surface soils and subsoils, respectively.

contents of the soil samples were determined according to the methods described by Brupbacher, et al. (1968). Phosphorus was extracted from the soil samples with a 0.10 *N* HC1 solution containing 0.03 *N* ammonium fluoride at a soil-to-solution ratio of 1:20. The concentration of P was determined on an aliquot of the soil extract after a blue color was developed upon adding a solution containing ammonium molybdate, sulphuric acid, boric acid, and a solution containing stannous chloride. The intensity of the color developed was measured on a Bausch and Lomb Spectrometer. Potassium, Ca, and Mg were extracted with a 0.10 *N* HC1 solution at a soil-to-extracting-solution ratio of 1:20 and determined using a Perkin-Elmer Model 303 Atomic Absorption Spectrophotometer.

A Leeds and Northrup glass electrode pH meter was used to measure the soil reaction. A slurry of soil and distilled water at a soil-to-solution ratio of approximately 1:1 was employed.

A procedure described by Jackson (1958) using 1 *N* ammonium acetate adjusted to pH 7.0 was employed for determination of cation exchange capacity. Ten percent potassium chloride was used to displace ammonium ions adsorbed by the exchange complex. Exchangeable soil cations were determined using a Perkin-Elmer Model 303 Atomic Absorption Spectrophotometer, and the percent base saturation was calculated by dividing the sum of the soil cations by the cation exchange capacity and multiplying by 100.

Five extracting solutions were compared to evaluate the S status of the selected soil samples. The extracting solutions were distilled water,

Table 3.—Rates of dolomitic limestone, phosphorus, and potassium applied to each surface and subsoil used in the greenhouse investigation

Sample number	Soil type	Dolomitic limestone[1]	P[2]	K[3]
		----------Kg per hectare ----------		
1 A[4]	Commerce sil	----	24	46
1 B[4]	sicl	----	24	46
2 A	Mhoon sicl	----	24	46
2 B	sic	----	24	46
3 A	Sharkey c	----	24	46
3 B	c	----	24	46
4 A	Gallion l	2240	24	93
4 B	scl	4480	24	93
5 A	Gallion vfsl	1120	49	93
5 B	scl	1120	49	93
6 A	Hebert vfsl	----	49	93
6 B	sicl	1120	49	93
7 A	Norwood sil	----	24	70
7 B	sil	----	24	70
8 A	Yahola sil	----	24	93
8 B	sil	----	24	93
9 A	Bowie fsl	3360	98	186
9 B	scl	3360	98	186
10 A	Gilead ls	1120	98	186
10 B	ls	1120	98	186
11 A	Ruston fsl	----	98	186
11 B	sc	2240	98	186
12 A	Acadia sil	1120	98	46
12 B	sicl	4480	98	46
13 A	Stough fsl	3360	98	186
13 B	cl	3360	98	186
14 A	Crowley sil	----	98	186
14 B	sicl	----	98	186
15 A[4]	Crowley sil	560	98	186
15 B[4]	sicl	----	98	186
16 A	Midland sil	----	49	186
16 B	sicl	2240	98	186
17 A	Morey sil	----	98	93
17 B	sicl	----	98	93
18 A	Jeanerette sil	1120	98	70
18 B	sicl	----	98	70
19 A	Loring sil	1120	98	186
19 B	sicl	4480	98	186
20 A	Memphis sil	560	24	186
20 B	sicl	3360	24	186

(Continued)

Table 3.—(Continued)

Sample number	Soil type	Dolomitic limestone[1]	P[2]	K[3]
		----------Kg per hectare ----------		
21 A	Olivier sil	1120	49	70
21 B	sicl	2240	24	70
22 A	Patoutville sil	2240	98	93
22 B	sicl	1120	98	93
23 A	Providence sil	----	98	186
23 B	sicl	3360	98	186

[1]The dolomitic limestone contained 52.5 percent $CaCO_3$ and 42 percent $MgCO_3$

[2]Reagent grade monocalcium phosphate, $Ca(H_2PO_4)_2 \cdot H_2O$, containing 25% P served as the source of P.

[3]Reagent grade potassium chloride, KCl, containing 52.4 percent K served as the source of K.

[4]A and B represent surface soils and subsoils, respectively.

pH 7.0 (Ensminger, 1954); 0.15 percent calcium chloride, pH 6.6 (Williams and Steinbergs, 1964); 0.5 *N* ammonium acetate containing 0.25 *N* acetic acid, pH 5.0 (Bardsley and Lancaster, 1960); monocalcium phosphate containing 500 ppm of P, pH 2.8 (Fox et al., 1964); and 0.5 *M* sodium bicarbonate, pH 8.3 (Kilmer and Nearpass, 1960). The extraction procedures of Ensminger (1954), Williams and Steinbergs (1964), and Fox, et al. (1964) employed a soil-to-extracting-solution ratio of 1:5 and an extraction time of 30 minutes. The Bardsley and Lancaster (1960) extraction procedure required a 1:2.5 soil-to-extracting-solution ratio and an extraction time of 30 minutes. A soil-to-extracting-solution ratio of 1:4 and an extraction time of 60 minutes was employed by the Kilmer and Nearpass (1960) procedure. Colloidal material present in the distilled water extracts was removed using "Norit A" type activated charcoal as described by Bardsley and Lancaster (1960). An aliquot of the sodium bicarbonate soil extracts, which contained solubilized organic compounds that interfered with the precipitation of the barium sulphate, was digested with a 2:1 mixture of nitric and perchloric acids to oxidize the organic compounds extracted (Fox, et al., 1964).

Concentration of S in soil extracts was determined by the turbidimetric procedure proposed by Bardsley and Lancaster (1960). An aliquot of the soil extracts was acidified with a 1:1 solution of distilled water and HCl, and the sulphates were precipitated as barium sulphate by the addition of barium chloride crystals. The turbidity of the barium sulphate suspension was measured using a Bausch and Lomb Spectrophotometer.

A dry combustion procedure described by Allison, et al. (1965) was employed for the determination of the organic carbon content of the soil

samples. Carbonates present in the calcareous alluvial soils were removed prior to combusion by the procedure described by Piper (1944). The total N content of the soil samples was determined by the Kjeldahl method modified by Meeker and Wagner (1933).

The total S content of the soil samples was oxidized to sulphate-S (SO_4–S) by digestion with a mixture of nitric, perchloric, and phosphoric acids according to the method described by Arkley (1961). The SO_4–S in solution was determined by the turbidimetric procedure proposed by Bardsley and Lancaster (1960).

This method was used for the determination of the soil S and reserve S contents of the soil samples. Soil S was determined by igniting a mixture of soil and sodium bicarbonate in a muffle furnace at 500°C. The S liberated from the oxidation of organic compounds and the soluble SO_4–S was extracted with a sodium phosphate-acetic acid solution and determined turbidimetrically. Reserve S was obtained by the difference between soil S and soluble SO_4–S extracted with a 0.5 *N* ammonium acetate solution containing 0.25 *N* acetic acid.

A measure of organic S was obtained by an ignition procedure described by Bardsley and Lancaster (1965). Prior to ignition sulphides were converted to hydrogen sulphide (H_2S) by treating the soil samples with a 1.0 *N* HCl solution, and soluble SO_4–S was removed from the soil samples by leaching with a 1.0 *N* calcium acetate solution. The organic S was oxidized to SO_4–S by igniting a mixture of soil and sodium bicarbonate in a muffle furnace at 500°C. The soluble SO_4–S liberated was extracted with a sodium phosphate-acetic acid solution and determined turbidimetrically.

HI-reducible S was determined by a method proposed by Freney (1961). Soil samples were digested with a mixture of hydriodic, formic, and hypophosphorus acids in a Johnson and Nishita (1952) digestion-distillation apparatus (Figure 1) using their procedure. The H_2S liberated was reacted with zinc acetate to form zinc sulphide. The H_2S was subsequently released by acidification of the zinc sulphide solution and reacted with p-aminodimethylaniline to form methylene blue. The intensity of the methylene blue color developed was measured colorimetrically using a Bausch and Lomb Spectrophotometer.

The procedure described by Lowe and DeLong (1963) was used for the determination of the carbon-bonded S content of the soil samples. The 50-ml digestion flask of the Johnson and Nishita (1952) digestion-distillation apparatus was replaced by one of 150-ml capacity for the determination of carbon-bonded S. A 0.5-g soil sample, 0.1 g of 50 percent nickel-aluminum alloy, 5 ml of 5 percent sodium hydroxide, and 25 ml of distilled water were placed in the digestion flask. After a 30-minute digestion over low heat, the flask was removed and allowed to

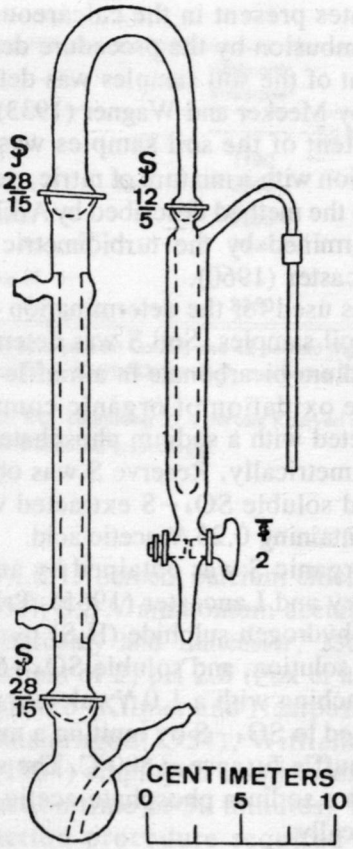


Fig. 1.—Digestion-distillation apparatus used for the determination of HI-reducible sulphur and carbon-bonded sulphur.

cool, and 5 ml of 1:1 HCL was added. The flask was rapidly reconnected to the digestion-distillation apparatus and distilled for an additional 30 minutes. A methylene blue color developed as described by Johnson and Nishita (1952).

Yield data and plant chemical analytical data were statistically analyzed by the analysis of variance method described by Steel and Torrie (1960). The t-test was employed to determine significance between treatments. Relative yield was calculated by dividing yield obtained when S was not applied by yield obtained when S was applied and multiplying by 100.

Results and Discussion

Effects of application of S on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Mississippi, Ouachita, and Red River Alluvial Areas are presented in Tables 4 through 6.

Yield of sudangrass-sorghum hybrid grown on Mhoon surface soil and Sharkey surface soil was significantly increased by application of 56 kg S per hectare (Table 4). The S concentration in plants grown on Mhoon surface soil that did not receive an application of S was 0.15 percent, and 37 mg of S were absorbed from the soil by the forage. Concentration and uptake of S by plants grown on Mhoon surface soil were considerably higher than for plants grown on Sharkey surface soil. Forage grown on Mhoon surface soil absorbed more than twice as much S as did forage grown on Sharkey surface soil.

Sudangrass-sorghum hybrid grown on Mhoon surface soil and subsoil absorbed more S, P, and Mg than did sudangrass-sorghum hybrid grown on Commerce surface soil and subsoil or Sharkey surface and subsurface soil. The greater amounts of S, P, and Mg absorbed by plants grown on Mhoon surface and subsurface soil may be attributed to higher yields of forage obtained on these soils.

Table 4.—Effects of applications of sulphur on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Mississippi River Alluvial Area

Sample number	Soil type	S treatments[1]	Total yield[2]	Concentration				Uptake			N:S ratio
				S	P	Mg	N	S	P	Mg	
			g/pot	%				mg/pot			
1 A[3]	Commerce sil	No S	21.1	0.15	0.25	0.66	2.5	32.0	52.2	140.6	16.3
		S	20.0	0.21	0.24	0.64	2.7	42.4	47.8	128.2	12.5
1 B[3]	Commerce sicl	No S	12.3	0.14	0.17	0.54	2.4	17.7	21.4	66.2	16.4
		S	11.5	0.19	0.21	0.65	2.8	21.8	23.9	74.5	14.1
2 A	Mhoon sicl	No S	25.1	0.15	0.38	0.54	2.7	37.1	94.8	134.6	18.4
		S	28.9**	0.28	0.34	0.48	2.7	81.1	98.8	138.6	9.5
2 B	Mhoon sic	No S	24.7	0.14	0.27	0.64	2.5	35.7	67.0	158.0	17.0
		S	23.7	0.19	0.29	0.63	2.5	44.2	69.3	149.2	13.6
3 A	Sharkey c	No S	15.9	0.10	0.47	0.37	2.4	15.2	74.6	59.2	25.3
		S	21.1**	0.22	0.33	0.41	2.7	46.4	69.7	86.1	12.1
3 B	Sharkey c	No S	12.4	0.11	0.25	0.46	2.3	14.1	30.8	56.8	20.2
		S	14.0	0.15	0.23	0.47	2.3	21.5	32.4	66.2	14.8

[1]S was applied at a rate equivalent to 56 Kg per hectare as Na_2SO_4 (22.5 percent S).

[2]Total yield consisted of three harvests.

[3]A and B represent surface soils and subsoils, respectively.

**Denotes that the yield of the S treatment was significantly higher than the yield of the no S treatment at the 1 percent level of probability.

Sudangrass-sorghum hybrid grown on Commerce surface soil or Commerce, Mhoon, and Sharkey subsoils did not respond to application of S. Although a significant yield response to applied S was not obtained, forage grown on Sharkey subsoil contained a relatively low concentration of total S (0.11 percent), and the N:S ratio in the tissue was relatively wide (20.2:1). The concentrations of S in plants grown on Commerce surface soil and Commerce and Mhoon subsoils were 0.15, 0.14, and 0.14 percent, respectively, and the N:S ratios were 16.3:1, 16.4:1, and 17.0:1, respectively.

Application of S significantly increased yield of sudangrass-sorghum hybrid grown on Gallion surface soil (Sample Number 4A) and Gallion subsoil (Sample Number 4B) (Table 5). Forage grown on Gallion surface soil (Sample Number 5A) did not respond to application of S; however, a significant yield response to applied S by forage grown on Gallion subsoil (Sample Number 5B) was obtained. Application of 56 kg per hectare of S significantly increased yield of sudangrass-sorghum hybrid grown on Hebert surface soil and subsoil by 43 and 67 percent, respectively.

Sudangrass-sorghum hybrid grown on soils from the Ouachita River Alluvial Area that contained a concentration of S equal to or less than 0.12 percent was deficient in S. The N:S ratios of the forages deficient

Table 5.—Effects of applications of sulphur on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Ouachita River Alluvial Area

Sample number	Soil type	S treatments[1]	Total yield[2]	Concentration				Uptake			N:S ratio
				S	P	Mg	N	S	P	Mg	
			g/pot	%				mg/pot			
4 A	Gallion 1	No S	14.2	0.09	0.45	0.66	2.7	12.8	63.7	93.7	29.6
		S	24.4**	0.27	0.30	0.78	2.3	66.0	74.6	190.4	8.7
4 B	Gallion scl	No S	11.6	0.11	0.20	0.73	2.4	12.3	23.2	84.6	23.0
		S	17.8**	0.15	0.16	0.74	2.4	26.0	28.0	130.5	16.3
5 A	Gallion vfsl	No S	17.9	0.16	0.40	0.78	2.7	29.4	72.3	140.0	16.5
		S	18.2	0.22	0.40	0.73	2.8	39.5	73.5	132.7	13.0
5 B	Gallion scl	No S	16.4	0.10	0.42	0.92	2.2	16.8	69.6	152.0	21.8
		S	20.0**	0.17	0.34	0.88	2.4	33.6	68.9	176.2	14.2
6 A	Hebert vfsl	No S	14.3	0.10	0.57	0.58	2.6	13.7	81.6	83.2	27.6
		S	20.4**	0.21	0.53	0.73	3.0	43.6	108.1	148.7	13.9
6 B	Hebert sicl	No S	14.2	0.10	0.41	0.68	2.0	13.5	58.2	97.2	20.6
		S	23.7**	0.16	0.38	0.76	2.1	38.2	90.1	180.5	13.1

[1]S was applied at a rate equivalent to 56 Kg per hectare as Na_2SO_4 (22.5 percent S).

[2]Total yield consisted of three harvests.

[3]A and B represent surface soils and subsoils, respectively.

** Denotes that the yield of the S treatment was significantly higher than the yield of the no S treatment at the 1 percent level of probability.

in S ranged from 20.6:1 (Sample Number 6B) to 29.6:1 (Sample Number 4A). Application of S to Gallion surface soil (Sample Number 5A) did not significantly increase yield of sudangrass-sorghum hybrid. Concentration of S and the N:S ratio in forage grown on Gallion surface soil (Sample Number 5A) were 1.16 percent and 16.5:1, respectively.

The amount of indigenous soil S absorbed by plants grown on soils deficient in S ranged from 12.3 to 16.8 mg. Application of S to all soils from the Ouachita River Alluvial Area resulted in significant increases in uptake of S by sudangrass-sorghum hybrid. The percentage increases in amounts of S absorbed by plants resulting from S treatments varied from 34 percent (Sample Number 5A) to 416 percent (Sample Number 4A).

The effects of applications of S on the yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Red River Alluvial Area are presented in Table 6. S treatments did not significantly increase the yield of the hybrid grown on the Norwood surface soil or the Norwood subsoil. Relatively low yields obtained on Norwood surface soil were thought to be due to a deficiency of one or more of the essential micronutrient elements. Leaf blades of plants grown on the Norwood surface soil exhibited an interveinal chlorosis indicative of zinc deficiency. Chlorosis was observed on plants grown in pots, and S treatment was not associated with the abnormality. Application of S to Norwood surface soil resulted in a relatively small increase in the concentration and the uptake of S by plants.

Yield of sundangrass-sorghum hybrid grown on Yahola surface soil was increased by approximately 122 percent as a result of application of 56 kg

Table 6.—The effects of applications of sulphur on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Red River Alluvial Area

Sample number	Soil type	S treatments[1]	Total yield[2]	Concentration				Uptake			N:S ratio
				S	P	Mg	N	S	P	Mg	
			g/pot	%				mg/pot			
7 A	Norwood sil	No S	6.0	0.18	0.23	0.50	3.3	11.0	14.2	30.3	18.3
		S	6.1	0.22	0.22	0.50	3.0	13.3	13.9	31.1	13.9
7 B	Norwood sil	No S	13.2	0.14	0.23	0.90	2.8	18.3	31.0	118.9	20.1
		S	14.1	0.16	0.21	0.85	2.8	23.1	29.6	119.2	17.0
8 A	Yahola sil	No S	9.2	0.12	0.51	0.75	3.0	11.2	46.8	69.6	24.8
		S	20.4**	0.21	0.37	0.89	2.8	42.2	76.3	182.1	13.6
8 B	Yahola sil	No S	6.4	0.12	0.30	0.69	2.6	7.5	19.1	44.0	22.4
		S	10.8**	0.19	0.30	0.80	2.7	20.4	32.3	86.7	14.2

[1]S was applied at a rate equivalent to 56 Kg per hectare as Na_2SO_4 (22.5 percent S).

[2]Total yield consisted of three harvests.

[3]A and B represent surface soils and subsoils, respectively.

**Denotes that the yield of the S treatment was significantly higher than the yield of the no S treatment at the 1 percent level of probability.

per hectare of S. Application of S resulted in a 69 percent increase in yield of forage grown on Yahola subsoil. S treatments significantly increased concentration and uptake of S by plants grown on Yahola surface soil and subsoil. When S was not applied, concentration of S in forage grown on both Yahola surface soil and subsoil was 0.12 percent, and N:S ratios in plant tissue were 24.8:1 and 22.4:1, respectively. Forage grown on Yahola surface soil and Yahola subsoil absorbed 11.2 and 7.5 mg of indigenous soil S, respectively.

Effects of applications of S on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Coastal Plain and Flatwoods Areas are presented in Table 7. Yields of sudangrass-sorghum hybrid grown on Bowie surface soil, Gilead surface soil, Gilead subsoil, and Stough subsoil were significantly increased by application of 56 kg S per hectare. S treatments did not significantly affect yield of plants

Table 7.—The effects of applications of sulphur on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Coastal Plain and Flatwoods Areas

Sample number	Soil type	S treatments[1]	Total yield[2]	Concentration				Uptake			N:S ratio
				S	P	Mg	N	S	P	Mg	
			g/pot	%				mg/pot			
9 A[3]	Bowie fsl	No S	12.8	0.11	0.33	0.95	3.1	14.4	41.9	121.8	27.8
		S	17.8**	0.20	0.25	1.01	3.1	36.4	44.2	179.4	15.2
9 B[3]	Bowie scl	No S	12.9	0.15	0.20	1.00	2.6	18.8	26.0	129.0	18.1
		S	13.9	0.19	0.19	1.04	2.7	25.9	26.0	145.3	14.5
10 A	Gilead ls	No S	10.8	0.11	0.41	0.73	3.0	11.5	44.9	79.2	28.6
		S	15.1**	0.21	0.36	0.77	3.4	32.0	55.0	117.3	16.1
10 B	Gilead ls	No S	7.4	0.10	0.45	0.63	2.5	7.2	33.3	46.6	25.6
		S	14.3**	0.22	0.46	0.77	3.0	31.4	66.2	110.4	13.5
11 A	Ruston fsl	No S	17.8	0.17	0.23	0.89	3.3	30.0	41.5	158.4	19.7
		S	17.3	0.19	0.22	0.86	3.5	32.9	38.6	148.8	18.3
11 B	Ruston sc	No S	11.9	0.18	0.18	1.01	3.0	20.8	21.7	120.1	17.3
		S	13.2	0.19	0.17	0.98	2.9	25.0	22.4	129.8	15.3
12 A	Acadia sil	No S	23.1	0.16	0.26	0.77	3.0	36.2	60.5	179.1	19.3
		S	23.9	0.26	0.27	0.79	3.1	61.6	64.2	187.8	12.0
12 B	Acadia sicl	No S	7.8	0.17	0.11	0.64	2.8	13.0	8.4	49.9	17.0
		S	9.4	0.19	0.14	0.75	3.0	18.1	13.2	70.7	15.7
13 A	Stough fsl	No S	5.8	0.20	0.19	0.97	3.4	11.7	11.1	56.1	16.6
		S	5.7	0.22	0.20	0.86	3.8	12.7	11.3	49.6	17.2
13 B	Stough cl	No S	7.9	0.12	0.30	0.98	2.8	9.7	24.2	77.6	23.2
		S	11.5**	0.20	0.28	1.03	2.8	22.4	32.4	118.1	14.6

[1]S was applied at a rate equivalent to 56 Kg per hectare as Na_2SO_4 (22.5 percent S).

[2]Total yield consisted of three harvests.

[3]A and B represent surface soils and subsoils, respectively.

** Denotes that the yield of the S treatment was significantly higher than the yield of the No S treatment at the 1 percent level of probability.

grown on Ruston, Acadia, and Stough surface soils or Bowie, Ruston, and Acadia subsoils. An explanation is not given for the relatively low yields of plant material produced on Stough surface soil. The plants appeared to be stunted; however, visual plant nutrient deficiency symptoms were not observed.

Concentration of S in tissues of plants grown on soils deficient in S was 0.12 percent or less. N:S ratio of the S deficient tissue ranged from 23.2:1 (Stough subsoil) to 28.6:1 (Gilead surface soil). S content of forage grown on soils from the Coastal Plain and Flatwoods Areas that contained an adequate amount of indigenous soil S for maximum plant growth ranged from 0.15 percent (Bowie subsoil) to 0.20 percent (Stough surface soil), and the N:S ratio of these samples was less than 20:1.

The data presented in Table 8 show the effects of applications of S on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Coastal Prairies Area. S treatments did not significantly influence yield of forage grown on any soils from the Coastal Prairies Area. Relatively low concentrations of S were found in plants grown on Crowley surface soil and subsoil (Sample Numbers 14A and 14B), on Crowley subsoil (Sample Number 15B), and on Morey subsoil.

Table 8.—Effects of applications of sulphur on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Coastal Prairies Area

Sample number	Soil type	S treatments[1]	Total yield[2]	Concentration				Uptake			N:S ratio
				S	P	Mg	N	S	P	Mg	
			g/pot	%				mg/pot			
14 A[3]	Crowley sil	No S	19.1	0.18	0.32	0.89	3.2	34.5	60.6	169.4	18.0
		S	18.2	0.20	0.31	0.88	3.2	36.2	57.0	160.3	16.4
14 B[3]	Crowley sicl	No S	13.8	0.10	0.27	1.01	2.2	14.5	37.8	140.0	21.3
		S	14.8	0.14	0.24	0.97	2.2	21.1	34.9	143.9	15.3
15 A	Crowley sil	No S	16.3	0.17	0.23	0.68	3.1	28.2	37.4	111.4	18.0
		S	16.7	0.21	0.24	0.65	3.4	34.7	39.8	109.2	16.2
15 B	Crowley sicl	No S	17.4	0.11	0.29	0.88	2.3	18.9	51.2	152.9	21.5
		S	17.5	0.15	0.21	0.80	2.4	26.3	36.8	140.0	16.0
16 A	Midland sil	No S	20.2	0.17	0.32	0.87	2.7	34.9	64.3	176.6	15.5
		S	19.6	0.22	0.31	0.90	3.1	42.2	61.3	176.2	14.5
16 B	Midland sicl	No S	19.0	0.15	0.28	1.02	2.3	28.2	54.3	194.6	15.5
		S	18.4	0.18	0.27	0.98	2.5	32.6	48.9	179.3	14.2
17 A	Morey sil	No S	11.4	0.19	0.51	0.84	3.4	21.3	57.7	95.9	18.1
		S	10.5	0.20	0.58	0.74	3.6	20.9	60.9	77.2	18.1
17 B	Morey sicl	No S	17.1	0.12	0.35	0.97	2.4	21.1	60.5	165.7	19.7
		S	17.8	0.16	0.36	1.02	2.5	28.8	63.4	181.1	15.3

[1] S was applied at a rate equivalent to 56 Kg per hectare as Na_2SO_4 (22.5 percent S).

[2] Total yield consisted of three harvests. There were no significant differences in yield between the S treatments.

[3] A and B represent surface soils and subsoils, respectively.

The N:S ratio in tissues of plants grown on the two Crowley subsoils (Sample Numbers 14B and 15B) exceeded 21:1. The wide N:S ratios suggest that S content of these soils may be approaching a marginal level even though a yield response to application of S was not obtained.

Concentration of S in tissues of plants grown on soils from the Coastal Prairie Areas that did not receive supplemental S ranged from 0.10 to 0.19 percent. The amount of indigenous soil S absorbed by plants varied from 14.5 to 34.9 mg. Variation in amount of indigenous soil S absorbed by plants was due to differences in yield obtained on different soils and to variation that occurred in concentration of S in plant tissues.

Effects of applications of S on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Mississippi Terrances and Loessial Hills Areas are presented in Table 9. Application of 56 kg per hectare of S to Jeanerette surface soil resulted in a significant yield increase. Concentration of S in tissues of plants grown on Jeanerette surface soil that did not receive an application of S was 0.11 percent and the N:S ratio was 26.5:1.

Application of S resulted in a 179 percent increase in yield of forage grown on Jeanerette subsoil. Plants grown on Jeanerette subsoil that did not receive supplemental S contained only 0.06 percent S. Further evidence of severe S deficiency was the extremely wide N:S ratio of 44.4:1 in S-deficient plant tissue. Only 3.2 mg of S was absorbed by forage grown on Jeanerette subsoil.

S treatments had no significant effect on yield of sudangrass-sorghum hybrid grown on Loring, Memphis, Olivier, Patoutville, and Providence surface soils or subsoils.

Jeanerette subsoil was the only soil in which significant yield response to application of S was obtained at first harvest. Sudangrass-sorghum hybrid grown on the Jeanerette subsoil that did not receive an application of S failed to produce additional growth following second harvest.

Data presented in Tables 4 to 9 show that application of S increased concentration of S in tissues of plants grown on each of the 46 soils, and it also increased total uptake of S by sudangrass-sorghum hybrid. S concentration in tissues of plants grown on all soils that did not receive supplemental S ranged from 0.06 percent (Jeanerette subsoil) to 0.2 percent (Stough surface soil). With the exception of Mhoon surface soil, a significant yield response to applied S was not obtained if S concentration in forage exceeded 0.12 percent. S concentration in sudangrass-sorghum hybrid grown on Mhoon surface soil was 0.15 percent. Even though a statistically significant yield increase occurred on Mhoon soil following application of S, yield increase amounted to only 15 percent. The relatively low yield response indicates the soil may not be critically low in S.

Table 9.—Effects of applications of sulphur on yield and chemical composition of sudangrass-sorghum hybrid grown on selected soils of the Mississippi Terraces and Loessial Hills Areas

Sample number	Soil type	S treatments[1]	Total yield[2]	Concentration				Uptake			N:S ratio
				S	P	Mg	N	S	P	Mg	
			g/pot	%				mg/pot			
18 A[3]	Jeanerette sil	No S	18.9	0.11	0.34	0.92	3.0	21.5	63.5	173.7	26.5
		S	22.2*	0.25	0.32	0.90	3.2	56.4	71.3	198.6	12.4
18 B[3]	Jeanerette sicl	No S	5.7	0.06	0.41	0.64	2.4	3.2	23.7	36.5	44.4
		S	15.9**	0.18	0.26	0.93	2.5	28.4	41.4	148.3	13.8
19 A	Loring sil	No S	20.3	0.18	0.24	0.79	2.9	35.9	48.4	160.4	16.2
		S	20.3	0.20	0.21	0.72	3.0	39.5	42.6	145.9	15.1
19 B	Loring sicl	No S	18.3	0.15	0.15	0.91	2.3	28.0	28.2	166.1	15.1
		S	19.3	0.17	0.15	0.76	2.1	33.2	29.1	147.5	12.4
20 A	Memphis sil	No S	18.2	0.15	0.24	0.56	2.7	27.6	44.7	101.7	17.6
		S	16.7	0.18	0.31	0.55	2.7	30.7	52.4	91.6	14.9
20 B	Memphis sicl	No S	21.3	0.14	0.25	0.80	2.3	30.4	53.8	170.9	16.4
		S	20.9	0.16	0.25	0.78	2.5	32.8	51.4	162.1	15.6
21 A	Olivier sil	No S	21.1	0.15	0.30	0.63	2.6	31.7	62.3	133.5	19.6
		S	22.6	0.22	0.33	0.65	2.7	49.4	73.8	147.0	13.1
21 B	Olivier sicl	No S	17.5	0.16	0.15	0.66	2.7	27.7	25.8	115.6	14.4
		S	17.5	0.17	0.16	0.64	2.9	28.9	28.4	112.6	15.0
22 A	Patoutville sil	No S	18.6	0.14	0.26	0.94	3.0	27.0	47.7	174.7	19.5
		S	17.7	0.22	0.30	0.99	3.4	39.2	53.4	174.8	18.1
22 B	Patoutville sicl	No S	17.8	0.13	0.24	0.72	2.5	23.2	42.6	128.3	15.6
		S	18.8	0.16	0.21	0.73	2.6	30.1	39.3	136.7	14.6
23 A	Providence sil	No S	13.8	0.18	0.26	0.92	3.3	24.8	35.6	127.6	18.4
		S	15.2	0.19	0.25	0.93	3.2	29.5	37.7	140.7	15.8
23 B	Providence sicl	No S	12.6	0.16	0.15	1.06	2.8	20.4	19.4	132.8	15.9
		S	14.2	0.18	0.17	0.95	2.5	25.1	24.6	134.3	12.6

[1]S was applied at a rate equivalent to 56 Kg per hectare as Na_2SO_4 (22.5 percent S).

[2]Total yield consisted of three harvests.

[3]A and B represent surface soils and subsoils, respectively.

* **Denotes that the yield of the S treatment was significantly higher than the yield of the No S treatment at the 5 percent and 1 percent levels of probability, respectively.

A regression curve illustrating the relationship between relative yield and concentration of S in sudangrass-sorghum hybrid grown on all surface soils and subsoils is presented in Figure 2. A significant positive correlation coefficient ($R = 0.763$) was found between relative yield and S concentration in plant tissues. Ulrich and Hills (1967) stated that the concentration of any essential plant nutrient element at which growth is reduced by 10 percent can be considered the critical concentration. Critical concentration of S in sudangrass-sorghum hybrid grown on all soils used in the investigation was approximately 0.13 percent (Figure 2). Lancaster, et al. (1971) presented data which indicated that application of S to a Josephine surface

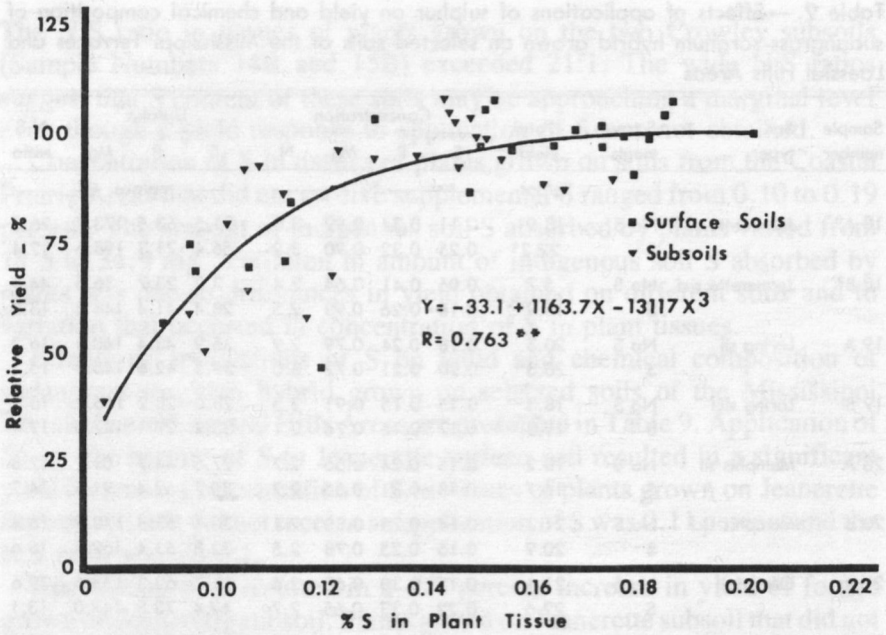


Fig. 2.—The relationship between relative yield and concentration of sulphur in sudangrass-sorghum hybrid grown on all surface soils and subsoils. (Relative yield—% = yield of No S treatment ÷ yield of S treatment x 100.) **Significant at the 1 percent level of probability.

soil from California did not result in an increase in yield of sudangrass if S concentration in the plant exceeded 0.1 percent.

The relationship between relative yield and N:S ratio in the sudangrass-sorghum hybrid grown on all surface soils and subsoils is presented in Figure 3. A significant negative correlation coefficient of −0.801 was found between these two variables. The data indicated that as the N:S ratio increased, a corresponding decrease in the relative yield was obtained. The regression equation presented in Figure 3 indicates the critical N:S ratio in the forage was 19.6:1. Ergle and Eaton (1951), Bardsley and Jordan (1957), Stewart and Whitfield (1965), an Lancaster, et al. (1971) reported that S became a limiting factor for maximum plant growth when N:S ratios in plant tissue were wider than 17:1 to 20:1.

N:S ratios in sudangrass-sorghum hybrid deficient in S ranged from 18:1 to 44:1 with a mean of 26:1. Application of 56 kg per hectare of S resulted in N:S ratios of 9:1 to 18:1 with a mean of 14:1. Bardsley and Jordan (1957) reported that N:S ratios of S-deficient clover averaged 24:1 and that the average N:S ratio of clover that received an adequate supply of S was 14:1.

Data shown in Figure 4 illustrate the effects of applications of S on concentrations of P and Mg in sudangrass-sorghum hybrid grown on soils deficient and sufficient in indigenous S. Application of 56 kg per hectare of S to soils deficient in S resulted in a significant reduction in concentration of P in plant tissue. Application of S to soils that contained sufficient S had

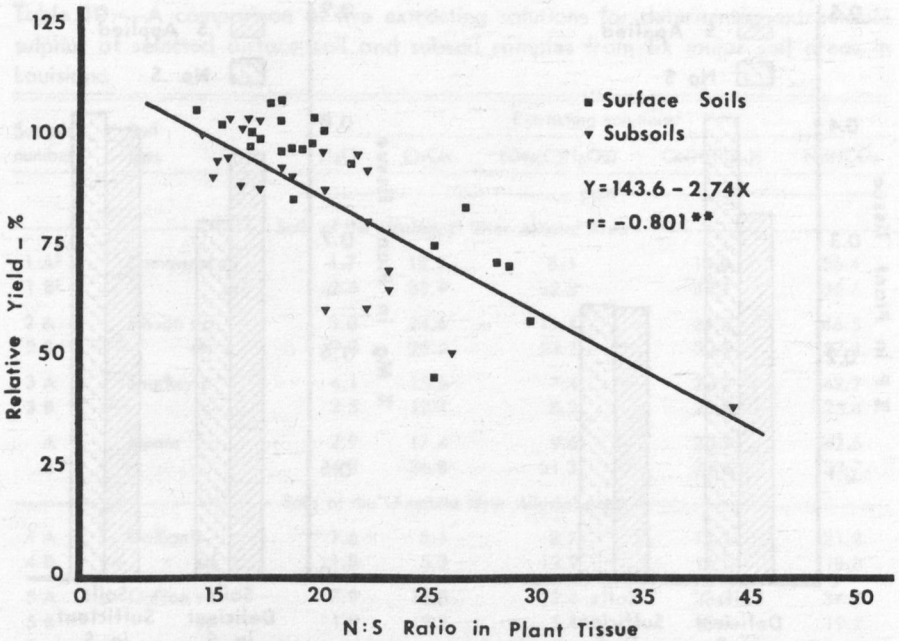


Fig. 3.—The relationship between relative yield and N:S ratio in sudangrass-sorghum hybrid grown on all surface soils and subsoils. (Relative yield—% = yield of No S treatment ÷ yield of S treatment x 100.) **Significant at the 1 percent level of probability.

no significant effect on concentration of P in plants. Forage grown on soils deficient in S contained significantly higher concentrations of P than forage grown on soils sufficient in S, regardless of S applications. Caldwell, et al. (1969) and Golden (1972) presented data which indicated that application of S reduced concentration of P in plant itssue.

Mg concentration in tissues of plants grown on soils deficient in S was significantly increased by application of S. The slight decrease in Mg concentration in forage grown on soils that contained a sufficient supply of indigenous S was not significant. Brupbacher and Sedberry (1965) reported that application of S increased the "availability" and absorption of indigenous soil Mg. Forage grown on soils supplied with sufficient amounts of S contained a higher concentration of Mg than was found in plants deficient in S. Results published by Anderson and Futral (1966) showed that S-deficient plants contained less Mg than plants supplied with S in amounts sufficient for maximum plant growth.

Five extracting solutions used for determination of S contents of selected surface soils and subsoils from six major soil areas in Louisiana were compared (Table 10). As an average of all surface soils and subsoils, the lowest mean concentration of extractable S (3.9 ppm) was obtained using water as the extracting solution. The greatest mean amount of S (36 ppm) was extracted with sodium bicarbonate solution. The average amounts of S

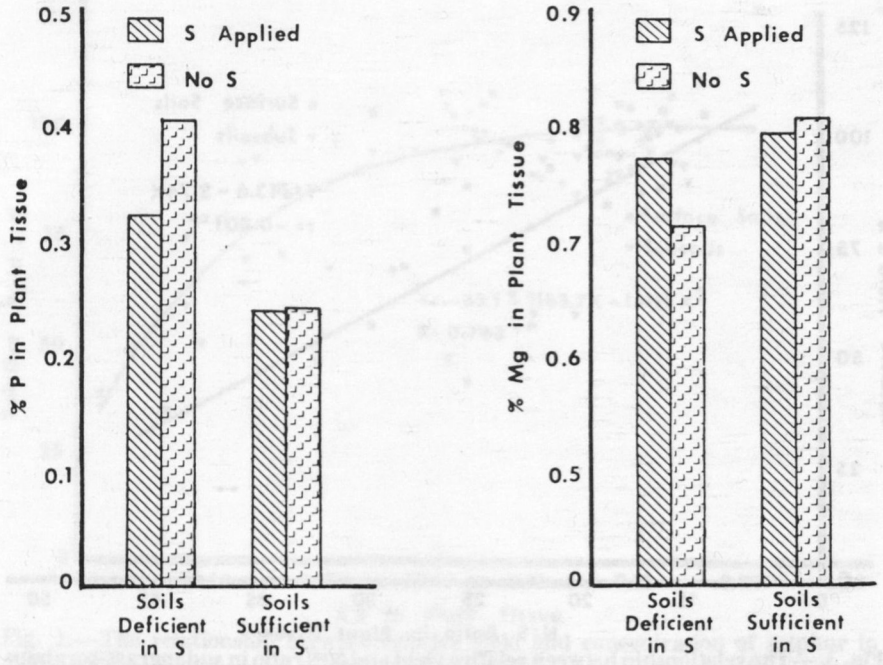


Fig. 4.—Effects of applications of sulphur on concentrations of phosphorus and magnesium in sudangrass-sorghum hybrid grown on soils deficient and sufficient in indigenous sulphur.

extracted from all surface soils and subsoils with calcium chloride, ammonium acetate, and calcium phosphate solutions were 12.5, 18.3, and 28.5 ppm, respectively. Jordan (1964) reported that the average sodium-bicarbonate-extractable S content of 21 surface soils from the southeastern United States was approximately three times that extracted with an ammonium acetate solution. Kilmer and Nearpass (1960) reported that a 0.5 *M* sodium bicarbonate solution extracts a fraction of the organic S present in soils in addition to soluble sulphates and adsorbed sulphates. Ensminger and Freney (1966) stated that soluble sulphates and adsorbed sulphates were extracted by acetate, phosphate, and bicarbonate solutions, whereas water and chloride solutions did not extract an appreciable quantity of adsorbed sulphates. Phosphate solutions were reported to be more effective in extraction of adsorbed sulphates than acetate solutions.

A comparison of the amounts of S extracted with calcium chloride and calcium phosphate solutions indicated that some subsoils of the Coastal Plain and Flatwoods Areas and the Mississippi Terraces and Loessial Hills Areas contained relatively large amounts of adsorbed sulphates. Subsoils from the Mississippi, Ouachita, and Red River Alluvial Areas and from the Coastal Prairies Area contained relatively small amounts of adsorbed

Table 10.—A comparison of five extracting solutions for determining extractable sulphur of selected surface soil and subsoil samples from six major soil areas in Louisiana

Sample number	Soil type	Extracting solutions[1]				
		H_2O	$CaCl_2$	$NH_4(C_2H_3O_2)$	$Ca(H_2PO_4)_2$	$NaHCO_3$
		ppm				
Soils of the Mississippi River Alluvial Area						
1 A[2]	Commerce sil	1.7	12.0	8.1	18.0	38.4
1 B[2]	sicl	2.6	33.9	32.8	39.7	35.6
2 A	Mhoon sicl	3.0	24.6	13.4	24.6	46.5
2 B	sic	9.3	28.2	23.1	30.9	37.1
3 A	Sharkey c	4.1	15.6	7.4	20.2	42.7
3 B	c	2.5	12.4	8.2	20.8	25.4
A	Means	2.9	17.4	9.6	20.9	42.5
B		4.8	24.8	21.3	30.5	32.7
Soils of the Ouachita River Alluvial Area						
4 A	Gallion l	1.6	8.5	8.7	14.1	21.8
4 B	scl	1.8	5.3	12.9	16.0	18.8
5 A	Gallion vfsl	7.2	15.8	12.4	23.7	34.8
5 B	scl	1.9	9.3	5.4	18.4	19.2
6 A	Hebert vfsl	2.1	15.5	6.2	24.8	28.2
6 B	sicl	1.6	6.9	4.6	12.8	13.4
A	Means	3.6	13.3	9.1	20.9	28.3
B		1.8	7.2	7.6	15.7	17.1
Soils of the Red River Alluvial Area						
7 A	Norwood sil	6.7	17.2	24.5	18.8	22.8
7 B	sil	4.1	12.0	15.2	20.7	16.6
8 A	Yahola sil	3.6	20.1	7.2	28.4	26.6
8 B	sil	2.4	10.6	4.8	20.1	13.6
A	Means	5.2	18.6	15.9	23.6	24.7
B		3.2	11.3	10.0	20.4	15.1
Soils of the Coastal Plain and Flatwoods Area						
9 A[2]	Bowie fsl	2.1	10.8	10.7	17.5	34.2
9 B[2]	scl	1.4	4.8	10.9	20.2	16.0
10 A	Gilead ls	1.8	12.5	8.0	10.1	17.6
10 B	ls	1.0	6.2	4.3	9.3	14.4
11 A	Ruston fsl	2.0	11.7	6.7	15.5	31.2
11 B	sc	9.7	8.6	118.9	121.0	149.6
12 A	Acadia sil	2.6	10.8	8.5	19.8	26.4
12 B	sicl	4.3	4.4	49.2	45.3	52.7
13 A	Stough fsl	2.5	19.3	30.0	31.5	43.3
13 B	cl	1.6	5.0	11.8	16.8	13.2
A	Means	2.2	13.0	12.8	18.9	30.6
B		3.6	5.8	39.0	42.5	49.2

(Continued)

Table 10.—(Continued)

Sample number	Soil type	Extracting solutions[1]				
		H_2O	$CaCl_2$	$NH_4(C_2H_3O_2)$	$Ca(H_2PO_4)_2$	$NaHCO_3$
		ppm				
Soils of the Coastal Prairies Area						
14 A	Crowley sil	8.3	16.0	13.1	17.6	25.8
14 B	sicl	2.9	6.8	6.4	12.9	14.6
15 A	Crowley sil	7.2	12.7	9.5	18.3	32.8
15 B	sicl	4.3	8.2	7.0	19.7	18.1
16 A	Midland sil	1.1	19.0	13.2	20.3	35.6
16 B	sicl	5.6	12.0	19.6	24.1	20.6
17 A	Morey sil	5.1	21.0	13.6	21.6	37.5
17 B	sicl	4.8	14.2	12.1	23.2	31.4
A	Means	5.4	17.2	12.4	19.4	32.9
B		4.4	10.3	11.3	20.0	21.2
Soils of the Mississippi Terraces and Loessial Hills Areas						
18 A[2]	Jeanerette sil	1.8	11.8	6.7	16.0	34.2
18 B	sicl	1.0	4.1	2.5	11.8	17.3
19 A	Loring sil	3.3	12.4	19.1	29.4	39.6
19 B	sicl	5.4	10.1	68.8	84.3	94.8
20 A	Memphis sil	5.0	10.4	9.5	21.6	30.5
20 B	sicl	11.2	31.5	95.0	115.5	128.5
21 A	Olivier sil	4.4	11.1	12.2	34.2	43.6
21 B	sicl	9.5	10.9	34.8	43.9	54.0
22 A	Patoutville sil	1.4	5.5	5.5	14.1	29.4
22 B	sicl	1.9	3.0	7.5	17.4	21.4
23 A	Providence sil	6.4	10.1	7.1	16.3	39.8
23 B	sicl	1.8	4.3	23.6	30.1	37.0
A	Means	3.7	10.2	10.0	21.9	36.2
B		5.1	10.6	38.7	50.5	58.8

[1]The extracting solutions, pH, and soil to extracting solution ratios used were as follows: water, pH 7.0, 1:5; calcium chloride, pH 6.6, 1:5; ammonium acetate, pH 5.0, 1:2.5; monocalcium phosphate, pH 2.8, 1:5; sodium bicarbonate, pH 8.3, 1:4.

[2]A and B represent surface soils and subsoils, respectively.

sulphates. Several investigators have reported that many subsurface horizons of Coastal Plain soils of the southeastern United States contain appreciable amounts of adsorbed sulphates (Ensminger, 1954; Jordan and Bardsley, 1958; Jordan, 1964; Kamprath, 1968).

Average concentrations of S extracted from surface soils with calcium phosphate solution were not appreciably different among soil areas (Table 10). Average calcium-phosphate-extractable S ranged from 18.9 ppm in soils from the Coastal Plain and Flatwoods Areas to 23.6 ppm in soils from

the Red River Alluvial Area. The amount of S extracted from subsoils with calcium phosphate solution varied considerably among different soil areas. Subsoils from the Ouachita River Alluvial Area averaged 15.7 ppm of S extracted with calcium phosphate solution, and subsoils from the Mississippi Terraces and Loessial Hills Areas averaged 50.5 ppm of calcium-phosphate-extractable S.

Relationships between S extracted from all surface soils with five extracting solutions are presented in Table 11. The highest correlation coefficient ($r = 0.558$) was obtained between calcium-phosphate- and sodium-bicarbonate-extractable S. S extracted from surface soils with distilled water was not related to the amounts of S extracted with any other extracting solutions.

Relationships between S extracted from all subsoils with five extracting solutions are presented in Table 12. Highly significant positive relationships were found between S extracted with distilled water and S extracted with calcium chloride, ammonium acetate, calcium phosphate, and sodium bicarbonate solutions. Significant positive relationships were also found between S extracted with calcium phosphate solution and that extracted with calcium chloride and ammonium acetate solutions. Correlation coefficients obtained between S extracted with sodium bicarbonate solution and ammonium-acetate- and calcium-phosphate-extractable S were 0.940 and 0.985, respectively. Calcium-chloride-extractable S was not significantly

Table 11.—Correlation coefficients indicating the relationships between sulphur extracted from all surface soil samples with five extracting solutions

Extracting solutions	Extracting solutions			
	H_2O	$CaCl_2$	$NH_4(C_2H_3O_2)$	$Ca(H_2PO_4)_2$
$CaCl_2$	0.180	-----	-----	-----
$NH_4(C_2H_3O_2)$	0.216	0.453*	-----	-----
$Ca(H_2PO_4)_2$	0.122	0.439*	0.486*	-----
$NaHCO_3$	0.022	0.303	0.242	0.558**

* **Significant at the 5 percent and 1 percent levels of probability, respectively.

Table 12.—Correlation coefficients indicating the relationships between sulphur extracted from all subsoil samples with five extracting solutions

Extracting solutions	Extracting solutions			
	H_2O	$CaCl_2$	$NH_4(C_2H_3O_2)$	$Ca(H_2PO_4)_2$
$CaCl_2$	0.543**	-----	-----	-----
$NH_4(C_2H_3O_2)$	0.743**	0.338	-----	-----
$Ca(H_2PO_4)_2$	0.755**	0.471*	0.931**	-----
$NaHCO_3$	0.707**	0.356	0.940**	0.985**

* **Significant at the 5 percent and 1 percent levels of probability, respectively.

related to S extracted with ammonium acetate or sodium bicarbonate solutions. In most instances, the relationship between the amounts of S extracted with various extracting solutions was higher for subsoils than it was for the surface soils.

A statistically significant relationship between yield response to application of S and the extractable-S content of surface soils was not obtained with any extracting solutions. A significant relationship was obtained between yield response to applied S and extractable-S content of subsoils with four extracting solutions. Significant positive correlation coefficients obtained between yield response to application of S and the amount of S extracted from subsoils with the distilled water, calcium chloride, ammonium acetate, and calcium phosphate solutions were 0.516, 0.535, 0.582, and 0.693, respectively. Sulphur extracted from subsoils with sodium bicarbonate solution was not related to yield. A better relationship was found between yield response to application of S and the extractable-S content of subsoils than was found for surface soils. This relationship may have been due to the wider range of extractable S and to a higher S content in subsoils.

The ammonium-acetate-extractable S content of the eight surface soils in which a yield response was obtained ranged from 6.2 to 13.4 ppm. Six of the eight soils contained less than 10 ppm of ammonium-acetate-extractable S. The ammonium-acetate-extractable S content of surface soils in which a yield response was not obtained ranged from 5.5 to 30.0 ppm. There were 15 surface soils that did not show a response to application of S, and seven of these contained less than 10 ppm of ammonium-acetate-extractable S. Jordan (1964) reported that the ammonium-acetate-extractable S content of 15 surface soils which exhibited yield responses to applied S ranged from 3 to 9 ppm. Six of the soils he used contained 6 ppm or less of ammonium-acetate-extractable S, and a yield response to application of S was not obtained.

Application of S to 7 of the 23 subsoils resulted in significant increases in yield of sudangrass-sorghum hybrid. These subsoils contained from 2.5 to 12.9 ppm of ammonium-acetate-extractable S. Two soils contained more than 10 ppm of S extracted with ammonium acetate. Only 4 of 15 subsoils that did not respond to application of S contained less than 10 ppm of extractable S. The ammonium-acetate-extractable S content of the 15 subsoils ranged from 6.4 to 118.9 ppm.

Surface soils or subsoils which contained more than 10 ppm of ammonium-acetate-extractable S generally did not respond to application of S; however, ammonium-acetate-extractable S was not satisfactory for prediction of yield responses if soils contained less than 10 ppm of extractable S. Jordan (1964) stated that ammonium-acetate- and sodium-bicarbonate-extractable S were satisfactory for identification of soils that were either well supplied with or seriously deficient in S for plant growth.

He reported that the methods were not satisfactory for determination of quanities of S available to plants in soils that were neither seriously deficient in nor well supplied with S.

The organic carbon (C) total N, total S, soil S, reserve S, organic S, HI-reducible S, and carbon-bonded S contents of selected surface soils and subsoils from six major soil areas in Louisiana are presented in Table 13. The organic C and total N contents of surface soils averaged 0.81 and 0.08 percent, respectively. The average organic C and total N contents of subsoils were 0.47 and 0.05 percent, respectively.

Total S content of surface soils ranged from a low of 81 ppm to a high of 370 ppm with a mean of 153 ppm. Subsoils averaged 167 ppm of total S and varied from 61 to 436 ppm. Soils of the Mississippi River Alluvial Area contained the highest mean concentration of total S, and the Ouachita River Alluvial soils contained the lowest mean concentration of total S. According to Nelson (1964), average total S content of 12 Mississippi surface soils was 124 ppm and varied from 60 to 282 ppm. Grava (1971) reported that Minnesota surface soils may contain from 300 to 700 ppm of total S.

Soil S content of surface soils, which is a measure of organic S plus sulphate-S, ranged from 52 to 228 ppm with a mean of 106 ppm, and the subsoils contained from 35 to 172 ppm of soil S and averaged 76 ppm. Reserve S content of surface soils and subsoils averaged 72 ppm, and the average organic S content of soils was 73 ppm. Bardsley and Lancaster (1960) reported that reserve S was essentially a measure of organic S, and this was further substantiated by Nelson (1964).

Organic-S content of surface soils ranged from a low of 37 ppm to a high of 215 ppm and averaged 96 ppm. Subsoils averaged 51 ppm of organic S and varied from 23 to 167 ppm. The Mississippi River Alluvial soils contained the highest mean concentration of organic S, and the smallest mean concentration of organic S was found in soils of the Ouachita River Alluvial Area. Average organic-S content of surface soils was 1.9 times as great as that found in subsoils. The relationship between organic S and total N contents of soils is presented in Figure 5. A highly significant correlation coefficient of 0.829 was found between the two variables. Bardsley and Lancaster (1960) obtained a highly significant correlation ($r = 0.933$) between total N and reserve-S contents of 23 Mississippi surface soils.

HI-reducible S content of surface soils averaged 69 ppm and varied from a low of 14 ppm to a high of 153 ppm. Subsoils averaged 53 ppm of HI-reducible S and ranged from 10 to 133 ppm. Surface soils contained a greater amount of HI-reducible S than did subsoils with the exception of the Ruston, Loring, Memphis, and Olivier series. The exceptions are due to the fact that large accumulations of adsorbed inorganic sulphate-S were concentrated in subsoil horizons of the soils. The greatest mean concentration of HI-reducible S was found in soils of the Mississippi River Alluvial

Table 13.—Organic carbon, total nitrogen, total sulphur, soil sulphur, reserve sulphur, organic sulphur, HI-reducible sulphur, and carbon-bonded sulphur contents of selected surface soil and subsoil samples from six major soil areas in Louisiana

Sample number	Soil type	Organic C	Total N	Total S	Soil S	Reserve S	Organic S	HI-reducible S	Carbon-bonded S
		%	%	ppm					
Soils of the Mississippi River Alluvial Areas									
1 A[1]	Commerce sil	0.52	0.06	184	74	66	67	62	21
1 B[1]	sicl	0.47	0.04	223	62	30	27	58	11
2 A	Mhoon sicl	0.95	0.12	359	225	212	215	134	77
2 B	sic	0.94	0.10	303	119	96	94	73	36
3 A	Sharkey c	1.38	0.14	370	228	221	215	153	92
3 B	c	1.00	0.10	355	172	164	167	112	43
A	Means	0.95	0.11	304	176	166	166	116	63
B		0.80	0.08	294	118	97	96	81	30
Soils of the Ouachita River Alluvial Area									
4 A	Gallion l	0.48	0.06	97	68	59	63	39	36
4 B	scl	0.16	0.04	140	44	31	34	21	16
5 A	Gallion vfsl	0.30	0.04	88	52	39	37	46	11
5 B	scl	0.28	0.03	85	41	35	33	36	10
6 A	Hebert vfsl	0.51	0.04	91	70	63	62	40	30
6 B	sicl	0.20	0.02	87	35	30	29	18	16
A	Means	0.43	0.05	92	63	54	54	42	26
B		0.21	0.03	104	40	32	32	25	14
Soils of the Red River Alluvial Area									
7 A	Norwood sil	0.56	0.07	152	121	97	102	97	29
7 B	sil	0.23	0.02	128	64	49	46	47	13
8 A	Yahola sil	0.38	0.04	97	82	74	78	48	37
8 B	sil	0.32	0.03	80	51	47	48	28	26
A	Means	0.47	0.06	124	102	86	90	72	33
B		0.26	0.02	104	58	48	47	38	20
Soils of the Coastal Plain and Flatwoods Areas									
9 A	Bowie fsl	1.30	0.07	94	88	77	81	51	34
9 B	scl	0.33	0.02	78	52	41	45	39	19
10 A	Gilead ls	0.64	0.05	81	68	60	67	14	32
10 B	ls	0.16	0.02	61	41	37	28	10	10
11 A	Ruston fsl	0.48	0.07	104	94	87	84	46	31
11 B	sc	0.34	0.03	291	144	25	29	129	9
12 A	Acadia sil	1.12	0.14	168	136	127	123	104	41
12 B	sicl	0.44	0.04	234	83	34	33	61	16
13 A	Stough fsl	0.95	0.05	114	97	67	64	60	23
13 B	cl	0.21	0.02	69	37	25	23	24	15
A	Means	0.90	0.10	112	97	84	84	55	32
B		0.30	0.03	147	71	32	32	53	14

(Continued)

Table 13.—(Continued)

Sample number	Soil type	Organic C	Total N	Total S	Soil S	Reserve S	Organic S	HI-reducible S	Carbon-bonded S
		%	%	ppm					
Soils of the Coastal Prairies Area									
14 A	Crowley sil	0.62	0.08	146	104	91	89	63	40
14 B	sicl	0.28	0.04	140	43	37	41	36	15
15 A	Crowley sil	0.69	0.08	155	93	83	81	64	32
15 B	sicl	0.37	0.06	144	44	37	36	35	18
16 A	Midland sil	1.30	0.10	167	106	93	91	69	27
16 B	sicl	0.99	0.09	138	67	48	49	55	23
17 A	Morey sil	0.99	0.08	172	153	140	141	80	59
17 B	sicl	0.76	0.06	141	98	86	84	58	31
A	Means	0.90	0.08	160	114	102	100	69	40
B		0.60	0.06	141	63	48	52	46	22
Soils of the Mississippi Terraces and Loessial Hills Areas									
18 A	Jeanerette sil	1.85	0.17	206	177	171	173	113	76
18 B	sicl	1.07	0.08	180	88	85	84	44	38
19 A	Loring sil	0.64	0.08	183	82	63	65	53	29
19 B	sicl	0.36	0.06	246	114	46	46	103	17
20 A	Memphis sil	0.40	0.05	134	56	46	44	51	21
20 B	sicl	0.37	0.06	436	147	52	53	133	19
21 A	Olivier sil	0.52	0.07	143	85	72	73	62	33
21 B	sicl	0.49	0.07	186	94	60	58	81	27
22 A	Patoutville sil	0.79	0.10	150	86	81	85	65	38
22 B	sicl	0.60	0.07	165	55	48	45	49	25
23 A	Providence sil	1.20	0.08	126	106	99	104	61	32
23 B	sicl	0.37	0.04	174	66	43	42	60	17
A	Means	0.90	0.09	157	99	89	91	68	38
B		0.54	0.06	231	94	56	55	78	24

[1] A and B represent surface soils and subsoils, respectively.

Area, and soils of the Ouachita River Alluvial Area contained the smallest mean concentration of HI-reducible S. A correlation coefficient of 0.915 was obtained between HI-reducible S and soil S contents of all of surface soils and subsoils. A regression curve illustrating the relationship between the two variables is presented in Figure 6.

Surface soils contained an average of 38 ppm of carbon-bonded S and ranged from a low of 11 ppm to a high of 92 ppm. The carbon-bonded S content of the subsoils varied from 9 to 43 ppm and averaged 20 ppm. Sharkey clay surface soil contained the highest content of carbon-bonded S (92 ppm), and the lowest concentration of carbon-bonded S (9 ppm) was found in Ruston sandy clay subsoil. As an average, surface soils contained

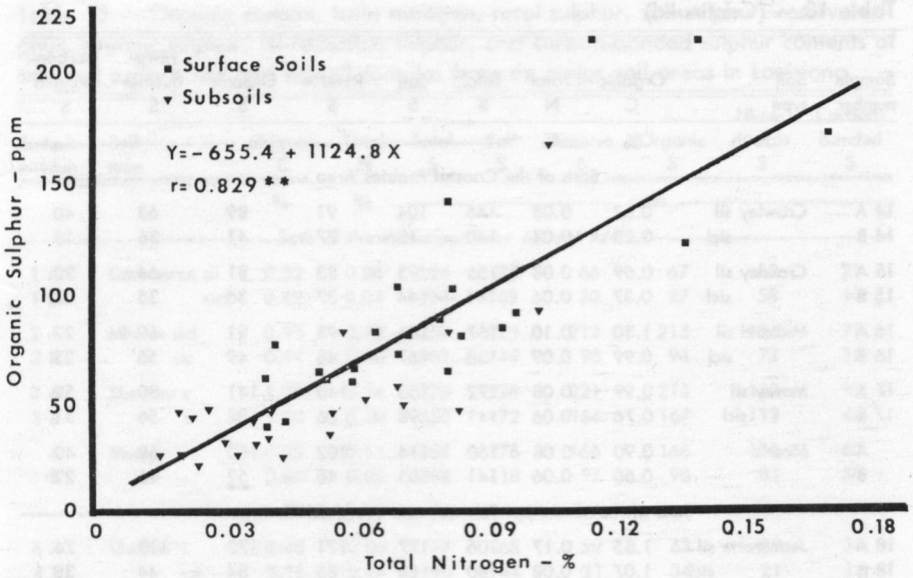


Fig. 5.—The relationship between organic sulphur and total nitrogen contents of surface soils and subsoils.

approximately twice the concentration of carbon-bonded S the subsoils did.

Relationships shown by correlation coefficients between organic C, total N, organic S, soil S, HI-reducible S, and carbon-bonded S contents of surface soils and subsoils are presented in Tables 14 and 15. Data presented in Table 14 indicate that highly significant relationships existed between each of the variables included in the investigation. The highest association was found between organic S and soil S content of surface soils ($r = 0.989$).

Data in Table 15 show that significant positive relationships existed among all the variables except HI-reducible S as related to organic C and carbon-bonded S. Data presented in Tables 14 and 15 indicate the close relationship between fractions of organic S, organic C, and total N.

Organic C, total N, and organic S ratios in selected surface soils and subsoils are shown in Table 16. Considerable variation was observed in the C:N, C:S, and N:S ratios of soils. Slightly more variation was observed among subsoils than among surface soils, and variation occurred within soil areas as well as between soil areas. Whitehead (1964) and Williams (1967) reviewed the literature on C, N, and S relationships in soils and stated that, although the mean C:S and N:S ratios for different groups of soils are remarkably similar, considerable variation in ratios occurs within each group.

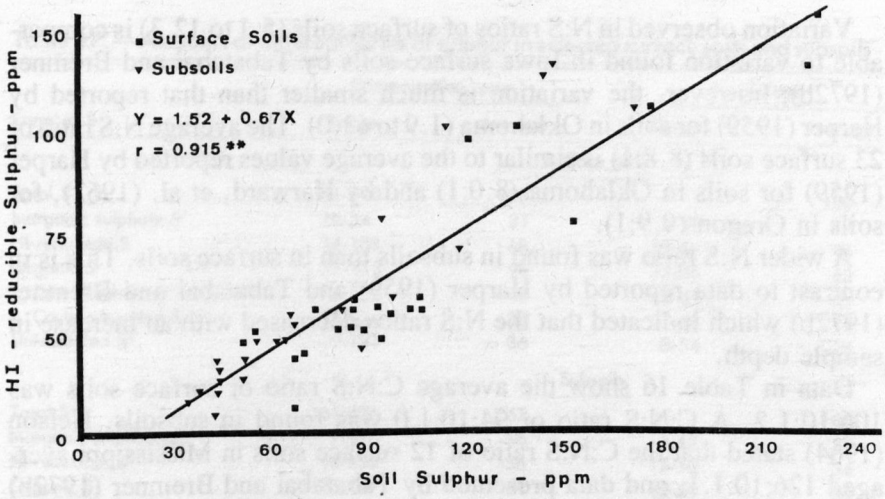


Fig. 6.—The relationship between HI-reducible sulphur and soil sulphur contents of surface soils and subsoils.

Table 14.—Correlation coefficients indicating relationships between organic carbon, total nitrogen, organic sulphur, soil sulphur, HI-reducible sulphur, and carbon-bonded sulphur contents of surface soils

	Chemical property				
Chemical property	Organic C	Total N	Organic S	Soil S	HI-reducible S
Total N	0.795**	----	----	----	----
Organic S	0.670**	0.809**	----	----	----
Soil S	0.662**	0.795**	0.989**	----	----
HI-reducible S	0.595**	0.812**	0.903**	0.929**	----
Carbon-bonded S	0.625**	0.764**	0.946**	0.922**	0.803**

**Significant at the 1 percent level of probability.

Table 15.—Correlation coefficients indicating relationships between organic carbon, total nitrogen, organic sulphur, soil sulphur, HI-reducible sulphur, and carbon-bonded sulphur contents of subsoils

	Chemical property				
Chemical property	Organic C	Total N	Organic S	Soil S	HI-reducible S
Total N	0.879**	----	----	----	----
Organic S	0.751**	0.730**	----	----	----
Soil S	0.509*	0.580**	0.666**	----	----
HI-reducible S	0.309	0.459*	0.419*	0.930**	----
Carbon-bonded S	0.835**	0.798**	0.881**	0.484**	0.225

* **Significant at the 5 percent and 1 percent levels of probability, respectively.

Variation observed in N:S ratios of surface soils (5.1 to 12.3) is comparable to variation found in Iowa surface soils by Tabatabai and Bremner (1972b); however, the variation is much smaller than that reported by Harper (1959) for soils in Oklahoma (1.9 to 63.0). The average N:S ratio of 23 surface soils (8.8:1) is similar to the average values reported by Harper (1959) for soils in Oklahoma (8.0:1) and by Harward, et al. (1962), for soils in Oregon (9.9:1).

A wider N:S ratio was found in subsoils than in surface soils. This is in contrast to data reported by Harper (1959) and Tabatabai and Bremner (1972b) which indicated that the N:S ratios decreased with an increase in sample depth.

Data in Table 16 show the average C:N:S ratio of surface soils was 106:10:1.2. A C:N:S ratio of 94:10:1.0 was found in subsoils. Nelson (1964) stated that the C:N:S ratio of 12 surface soils in Mississippi averaged 126:10:1.1, and data presented by Tabatabai and Bremner (1972b) indicated that the C:N:S ratio of 37 surface soils in Iowa averaged 109:10:1.5. Freney (1960) reported the average C:N:S ratio of eight surface soils in Australia was 113:10:1.2.

Data presented in Table 17 show the amounts of different forms of S in selected surface soils and subsoils. HI-reducible S accounted for an average of 44 and 34 percent of the total S present in the surface soils and subsoils, respectively. The percentages are somewhat lower than have been reported for Iowa surface soils (54 percent) and subsoils (72 percent) by Widdowson (1970).

Organic-S content in surface soils averaged 63 percent of the total S, and only 30 percent of the total S in subsoils was present as organic S. Nelson (1964) reported that organic-S content of 12 surface soils in Mississippi ranged from 26 to 91 percent of the total S and averaged 61 percent of the total S. As an average of all surface soils, 40 percent of the organic S was present as carbon-bonded S, and an average of 39 percent of the organic S

Table 16.—Organic carbon, total nitrogen, and organic sulphur ratios in surface soils and subsoils

	Range	Average
	Surface soils	
Carbon:nitrogen	6.9—18.6	10.2:1
Carbon:sulphur	44.2—106.7	88.1:1
Nitrogen:sulphur	5.1—12.3	8.8:1
Carbon:nitrogen:sulphur	----	106:10:1.2
	Subsoils	
Carbon:nitrogen	4.0—16.5	9.6:1
Carbon:sulphur	47.1—202.0	94.3:1
Nitrogen:sulphur	4.4—18.4	10.2:1
Carbon:nitrogen:sulphur	----	94:10:1.0

Table 17. —Amounts of different forms of sulphur in selected surface soils and subsoils

Form of S	Concentration, ppm		% of Total	
	Range	Average	Range	Average
		Surface soils		
Total S	81-370	153		100
Inorganic sulphate-S[1]	10-34	21	5-29	14
HI-reducible S	14-153	68	17-64	44
Organic S	37-215	96	33-86	63
Ester sulphate-S[2]	4-133	48	5-51	31
Carbon-bonded S	11-92	38	11-40	25
Unidentified S[3]	9-135	36	0-54	23
		Subsoils		
Total S	61-436	167		100
Inorganic sulphate-S[1]	9-175	36	6-42	22
HI-reducible S	10-133	56	15-50	34
Organic S	23-167	51	10-60	30
Ester sulphate-S[2]	1-91	23	2-26	14
Carbon-bonded S	9-43	20	3-32	12
Unidentified S[3]	12-267	80	15-70	48

[1] Inorganic sulphate-S extracted with a calcium phosphate solution containing 500 ppm of P.
[2] Ester sulphate-S calculated by subtracting inorganic sulphate-S from HI-reducible S.
[3] Unidentified S calculated by subtracting organic S and inorganic sulphate-S from total S.

present in the subsoils was in a carbon-bonded form. Carbon-bonded S accounted for an average of 25 and 12 percent of the total S present in the surface soils and subsoils, respectively. Widdowson (1970) reported that the total S content of selected Iowa surface soils contained an average of 8 percent carbon-bonded S, and the carbon-bonded S content of subsoils accounted for only 4 percent of the total S. Lowe and DeLong (1963) reported that 12 to 35 percent of the total S present in selected mineral soils of Quebec was in a carbon-bonded form. Correlation coefficients obtained between organic S and carbon-bonded S content of surface soils and subsoils were 0.946 and 0.881, respectively.

According to Tabatabai and Bremner (1972b), the fraction of organic S commonly described as ester sulphate-S may be calculated by subtracting inorganic sulphate-S from HI-reducible S. The values obtained for calcium-phosphate-extractable S were selected for calculation of ester sulphate-S because the other extracting solutions used in the investigation either extracted a portion of organic S or were not as effective in extraction of adsorbed sulphates as the phosphate solution (Ensminger and Freney, 1966). Ester sulphate-S content of the surface soils varied from 4 to 133 ppm and averaged 48 ppm. Subsoils averaged 23 ppm and ranged from 1 to 91 ppm. Ester sulphate-S accounted for an average of 31 and 14 percent of the total S present in surface soils and subsoils, respectively. An average of 50 percent of the organic S in surface soils was present as ester sulphate-S,

and ester sulphate-S accounted for 45 percent of the organic S present in subsoils.

An unidentified form of S is shown in Table 17. An average of 23 percent of the total S present in the surface soils could not be identified, and the unidentified fraction accounted for 48 percent of the total S in subsoils. Experimental evidence obtained in this investigation did not indicate whether the unidentified fraction of S was present as organic or inorganic S. Tabatabai and Bremner (1972b) reported that 36 percent of the total S in 37 Iowa surface soils could not be identified.

A significant relationship was not established between yield response to the application of S and total S, soil S, reserve S, organic S, HI-reducible S, or carbon-bonded S. Neither S uptake by sudangrass-sorghum hybrid nor percent S in plant tissues were related to the total S, soil S, reserve S, organic S, HI-reducible S, or carbon-bonded S content of the selected soils.

Summary and Conclusions

Greenhouse and laboratory investigations were conducted to determine the relationships among various sulphur (S) fractions of selected soils in Louisiana and yield of a sudangrass-sorghum hybrid. Soils selected for the investigation were representative of each major soil area of the state with the exception of the Coastal Marshlands.

Application of 56 kg per hectare of S resulted in significant increases in yield of sudangrass-sorghum hybrid grown on eight of the 23 surface soils. Plants grown on seven of the 23 subsoils responded to application of S. Application of S resulted in significant yield increases ranging from 15 to 179 percent.

Yield responses from application of S were significantly related to concentration of S in sudangrass-sorghum hybrid. Data indicated that the critical concentration of S in sudangrass-sorghum hybrid grown on all soils included in the investigation was approximately 0.13 percent. The concentration of S in the plants grown on soils that did not receive supplemental S ranged from 0.06 to 0.20 percent.

A highly significant negative correlation coefficient was obtained between yield responses to application of S and the N:S ratio in sudangrass-sorghum hybrid. The data suggested that an S deficiency may be suspected when the N:S ratio in forage exceeded approximately 20:1. The N:S ratios in the sudangrass-sorghum hybrid that was deficient in S ranged from 18:1 to 44:1 with a mean of 26:1. The application of S resulted in N:S ratios in plants ranging from 9:1 to 18:1.

The average amounts of S extracted with distilled water, calcium chloride, ammonium acetate, calcium phosphate, and sodium bicarbonate solutions were 3.9, 12.5, 18.3, 28.5, and 36.0 ppm, respectively. The data indicated that certain subsoils of the Coastal Plain and Flatwoods Areas and the Mississippi Terraces and Loessial Hills Areas contained large accumulations of adsorbed sulphate-S. Subsoils from the Mississippi, Ouachita, and Red River Alluvial Areas and from the Coastal Prairies Area appeared to contain relatively small amounts of adsorbed sulphate-S.

A statistically significant relationship was not obtained between yield responses to S application and the extractable-S contents of surface soils using any extracting solutions. A significant relationship was obtained between yield responses to application of S and the extractable S contents of subsoils with four extracting solutions. The correlation coefficients obtained between yield and the amounts of S extracted from subsoils with distilled water, calcium chloride, ammonium acetate, and calcium phosphate solutions were 0.516, 0.535, 0.582, and 0.693, respectively. In most instances, surface soils and subsoils which contained more than 10 ppm of ammonium-acetate-extractable S did not respond to application of S.

However, ammonium-acetate-extractable S was not satisfactory for the prediction of yield responses to application of S if the soils contained less than 10 ppm of extractable S.

Surface soils contained an average of 153 ppm of total S, and the average total S content of subsoils was 167 ppm. Of the total S present in surface soils, an average of 63 percent was organic S, 44 percent was HI-reducible S, 25 percent was carbon-bonded S, and 14 percent was calcium-phosphate-extractable sulphate-S. Organic S, HI-reducible S, carbon-bonded S, and calcium-phosphate-extractable susphate-S accounted for 30, 34, 13, and 22 percent of the total S present in subsoils, respectively.

The C:N:S ratio of surface soils was 106:10:1.2, and the C:N:S ratio of subsoils was 94:10:1.0. A highly significant correlation coefficient of 0.829 was obtained between total N and organic-S contents of soils. The average N:S ratios of surface soils and subsoils were 8.8:1 and 10.2:1, respectively.

Attempts were made to relate total S contents of soils, soil organic S, and various fractions of soil organic S to yield responses to application of S, S uptake by plants, and S concentration in plant tissues. A significant relationship among these factors could not be established.

The results indicated that total S and N contents in plant tissues and the N:S ratio were the most reliable laboratory diagnostic techniques for determination of the S status of soils. Data indicated that the extractable sulphate-S content of soils may be of some value in the prediction of a yield response to application of S if the soil is well supplied with S or severely deficient in S. Evidence was obtained which suggested the sulphate-S content of the subsoil should be included in an evaluation of the S status of soils since certain soils were found to contain large accumulations of adsorbed sulphate-S in lower horizons. Accumulations of adsorbed sulphate-S may supply S to plants in amounts sufficient for maximum yield even though the surface soil may be relatively low in S.

Literature Cited

Alexander, Martin. 1961. Introduction to soil microbiology. John Wiley and Sons, Inc. New York and London.

Allison, L. E., W. B. Bollen, and C. D. Moodie. 1965. Total carbon. *In* C. A. Black (ed.) Methods of soil analysis, Part II. Agronomy 9:1364-1366.

Alway, F. J. 1940. A nutrient element slighted in agricultural research. J. Amer. Soc. Agron. 32:913-921.

Anderson, O. E. and J. G. Futral. 1966. Sulfur and crop production in Georgia. Georgia Agr. Exp. Sta. Bull. 167.

Anonymous. 1967. Sulphur—the essential plant nutrient. The Sulphur Institute. Washington, D.C.

Arkley, T. H. 1961. Sulphur compounds of soil systems. Ph.D. Dissertation. University of California, Riverside, California.

Bardsley, C. E. and H. V. Jordan. 1957. Sulphur availability in seven southeastern soils as measured by growth and composition of white clover. Agron. J. 49:310-312.

Bardsley, C. E. and J. D. Lancaster. 1960. Determination of reserve sulfur and soluble sulfates in soils. Soil Sci. Soc. Amer. Proc. 24:265-268.

Bardsley, C. E. and J. D. Lancaster. 1965. Sulfur. *In* C. A. Black (ed.) Methods of soil analysis, Part II. Agronomy 9:1102-1116.

Barrow, N. J. 1961. Studies on mineralization of sulfur from soil organic matter. Australian J. Agr. Res. 12:306-319.

Beaton, J. D., G. R. Burns, and Jan Platou. 1968. Determination of sulphur in soils and plant material. Tech. Bull. 14. The Sulphur Institute. Washington, D.C.

Bentley, C. F., D. J. Hoff, and D. B. Scott. 1955. Fertilizer studies with radioactive sulphur. Can. J. Agr. Sci. 35:264-281.

Berg, W. A. and G. W. Thomas. 1959. Anion elution patterns from soils and soil clays. Soil Sci. Soc. Amer. Proc. 23:348-350.

Bertolacini, R. J. and J. E. Barney II. 1957. Colorimetric determination of sulphate with barium chloranilate. Anal. Chem. 29:281-283.

Bertramson, B. R., M. Fried, and S. L. Tisdale. 1950. Sulfur studies of Indiana soils and crops. Soil Sci. 70:27-41.

Bingham, F. T., J. R. Sims, and A. L. Page. 1965. Retention of acetate by montmorillonite. Soil Sci. Soc. Amer. Proc. 29:670-672.

Bledsoe, R. W. and R. E. Blaser. 1947. The influence of sulfur on the yield and chemical composition of clovers fertilized with different sources of phosphorus. J. Amer. Soc. Agron. 39:323-329.

Bonner, W. P. 1969. The effect of sulphur and liming materials on soil properties and yield and chemical composition of red clover. M.S. Thesis. Louisiana State University, Baton Rouge, Louisiana.

Borden, F. Y. and L. H. McCormick. 1970. An indirect method for the measurement of sulfate by barium absorption spectrophotometry. Soil Sci. Soc. Amer. Proc. 34:705-706.

Brupbacher, R. H., W. P. Bonner, and J. E. Sedberry, Jr. 1968. Analytical methods and procedures used in the soil testing laboratory. Louisiana Agr. Exp. Sta. Bull. 632.

Brupbacher, R. H. and J. E. Sedberry, Jr. 1965. Effects of magnesium and sulphur on the growth and chemical composition of clover on fourteen Coastal Plain soils in Louisiana. Louisiana Agr. Exp. Sta. Bull. 599.

Burns, G. R. 1967. Oxidation of sulphur in soils. Tech Bull. 13. The Sulphur Institute. Washington, D.C.

Caldwell, A. C., E. C. Seim, and G. W. Rehm. 1969. Sulphur effects on the elemental composition of alfalfa (*Medicago sativa* L.) and corn (*Zea mays* L.). Agron. J. 61:632-634.

Chang, M. L. and G. W. Thomas. 1963. A suggested mechanism for sulfate adsorption by soils. Soil Sci. Soc. Amer. Proc. 27:281-283.

Chao, T. T. 1964. Anionic effects on sulfate absorption by soils. Soil Sci. Soc. Amer. Proc. 28:581-583.

Chao, T. T., M. E. Harward, and S. C. Fang. 1962. Soil constituents and properties in the adsorption of sulfate ions. Soil Sci. 94:276-283.

Chesnin, Leon and C. H. Yien. 1951. Turbidimetric determination of available sulfates. Soil Sci. Soc. Amer. Proc. 15:149-151.

Conrad, J. P. 1950. Sulfur fertilization in California and some related factors. Soil Sci. 70:43-54.

DeLong, W. A. and L. E. Lowe. 1962. Note on carbon bonded sulphur in soil. Can. J. Soil Sci. 42:223.

Dymond, T. S., F. Hughes, and C. W. C. Jupe. 1905. The influence of sulphates as manures upon the yield and feeding value of crops. J. Agr. Sci. 1:217-229.

Eaton, S. V. 1922. Sulfur content of soils and its relation to plant nutrition. Bot. Gaz. 74:32-58.

Ensminger, L. E. 1954. Some factors affecting the absorption of sulfate by Alabama soils. Soil Sci. Soc. Amer. Proc. 18:259-264.

Ensminger, L. E. and J. R. Freney. 1966. Diagnostic techniques for determining sulfur deficiencies in crops and soils. Soil Sci. 101:283-290.

Erdmand, L. W. and W. B. Bollen, 1925. Field experiments with gypsum in Iowa. Iowa Agr. Exp. Sta. Bull. 232.

Ergle, D. R. and F. M. Eaton. 1951. Sulfur nutrition of cotton. Plant Physiol. 26:639-654.

Fox, R. L., R. A. Olsen, and H. F. Rhodes. 1964. Evaluating the sulphur status of soils by plant and soil tests. Soil Sci. Soc. Amer. Proc. 28:243-246.

Freney, J. R. 1958. Determination of water-soluble sulfate in soils. Soil Sci. 86:241-244.

Freney, J. R. 1960. The oxidation of cysteine to sulfate in soils. Australian J. Biol. Sci. 13:387-392.

Freney, J. R. 1961. Some observations on the nature of organic sulphur compounds in soil. Australian J. Agr. Res. 12:424-432.

Freney, J. R. 1962. Sulfur-containing organics. p. 229-259. *In* A. D. McLaren and G. H. Peterson (ed.) Soil Biochemistry. Marcel Dekker, Inc., New York.

Freney, J. R., N. J. Barrow, and K. Spencer. 1962. A review of certain aspects of sulphur as a soil constitutent and plant nutrient. Plant Soil. 17:295-308.

Freney, J. R., G. E. Melville, and C. H. Williams. 1969. Extraction, chemical nature and properties of soil organic sulphur. J. Sci. Fd. Agr. 20:440-445.

Golden, L. E. 1968. The relationship of sugarcane yields to the phosphorus and sulphur contents of certain Louisiana soils. Louisiana Agr. Exp. Sta. Bull. 633.

Golden, L. E. 1972. Relationship between fertilizer and leaf blade P and S and sugarcane yield in Louisiana. Proc. ISSCT 14:695-701.

Grafton, B. F. 1950. Sulfur as a nutrient element on Ruston loamy fine sand. M.S. Thesis. Louisiana State University, Baton Rouge, Louisiana.

Grava, John. 1971. The sulphur picture in Minnesota. Sulphur Inst. J. 7:12-14.

Harper, H. J. 1959. Sulfur content of Oklahoma soils, rainfall and atmosphere. Oklahoma Agr. Exp. Sta. Bull. B-536.

Harris, H. C., R. W. Bledsoe, and P. W. Calhoun. 1945. Responses of cotton to sulfur fertilization. J. Amer. Soc. Agron. 37:323-329.

Harward, M. E., T. T. Chao, and S. C. Fang. 1962. The sulfur status and sulfur supplying power of Oregon soils. Agron. J. 54:101-106.

Harward, M. E. and H. M. Reisenauer. 1966. Reactions and movement of inorganic soil sulfur. Soil Sci. 101:326-335.

Heinrich, B. J., M. D. Grimes, and J. E. Puckett. 1961. Sulfur. *In* I. M. Kolthoff and P. J. Elving (ed.) Treatise on analytical chemistry. Interscience Publishers, New York.

Hunter, B. 1909. Farm methods of applying land plaster in western Oregon and western Washington. US Dep. Agr. Circ. 22.

Jackson, M. L. 1958. Soil chemical analysis. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Jeane, M. D. 1954. The relationship of sulphur, phosphorus and magnesium in the growth and nutrition of white clover. M.S. Thesis. Louisiana State University, Baton Rouge, Louisiana.

Johnson, C. M. and H. Nishita. 1952. Microestimation of sulphur in plant materials, soils and irrigation waters. Anal. Chem. 24:736-742.

Jones, M. B. 1962. Total sulfur and sulfate sulfur content of subterranean clover as related to sulfur responses. Soil Sci. Soc. Amer. Proc. 26:482-484.

Jones, M. B. and W. E. Martin. 1964. Sulfate sulfur concentrations as an indicator of sulfur status in various California dryland pasture species. Soil Sci. Soc. Amer. Proc. 28:539-541.

Jordan, H. V. 1964. Sulfur as a plant nutrient in the southern United States. US Dep. Agr. Tech. Bull. 1297.

Jordan, H. V. and C. E. Bardsley. 1958. Responses of crops to sulfur on southeastern soils. Soil Sci. Soc. Amer. Proc. 22:254-256.

Kamprath, E. J. 1968. Sulphur reactions and availability in highly weathered soils. Sulphur Inst. J. 4:7-9.

Kamprath, E. J., W. L. Nelson, and J. W. Fitts. 1956. The effect of pH, sulfate and phosphate concentrations on the adsorption of sulfate by soils. Soil Sci. Soc. Amer. Proc. 20:463-466.

Kilmer, V. J. and D. C. Nearpass. 1960. The determination of available sulfur in soils. Soil Sci. Soc. Amer. Proc. 24:337-339.

Lancaster, D. L., M. B. Jones, J. H. Oh, and J. E. Ruckman. 1971. Effect of sulfur fertilization of forage species on yield, chemical composition and *In vitro* rumen microbial activity of sheep. Agron. J. 63:621-623.

Lobb, W. R. 1954. Sulphur investigations in North Otago. New Zeal. J. Agr. Res. 89:434-438.

Loosi, J. K. 1952. Methionine for growth of swine. Feed Age 2:44-45.

Lowe, L. E. 1964. An approach to the study of the sulphur status of soils and its application to selected Quebec soils. Can. J. Soil Sci. 44:176-179.

Lowe, L. E. and W. A. DeLong. 1963. Carbon bonded sulfur in selected Quebec soils. Can. J. Soil Sci. 43:151-155.

McMichael, C. W. 1949. Experiments with minor elements, p. 58-59. *In* Report of Projects, Department of Agronomy. Louisiana State University Agr. Exp. Sta.

Meeker, E. W. and E. L. Wagner. 1933. Titration of ammonia in presence of boric acid. Ind. Eng. Chem., Anal. Ed. 5:396-398.

Mehlich, A. 1964. Influence of sorbed hydroxyl and sulfate on neutralization of soil acidity. Soil Sci. Soc. Amer. Proc. 28:492-496.

Nearpass, D. C., M. Fried, and V. J. Kilmer. 1961. Greenhouse measurement of available sulfur using radioactive sulfur. Soil Sci. Soc. Amer. Proc. 25:287-289.

Neller, J. R. 1925. The influence of sulfur and gypsum upon the composition and yield of legumes. Washington Agr. Exp. Sta. Bull. 190.

Neller, J. R., G. B. Killinger, D. W. Jones, R. W. Bledsoe, and H. W. Lundy. 1951. Sulfur requirements of soils for pastures in relation to fertilizer phosphates. Florida Agr. Exp. Sta. Bull. 475.

Nelson, L. E. 1964. Status and transformation of sulfur in Mississippi soils. Soil Sci. 97:300-306.

Paul, E. A., and E. L. Schmidt. 1960. Extraction of free amino acids from soil. Proc. Soil Sci. Soc. Amer. 24:195.

Piper, C. W. 1944. Soil and plant analysis. Interscience Publishers, Inc., New York.

Pumphrey, F. V. and D. P. Moore. 1965. Diagnosing sulfur deficiency of alfalfa (*Medicago sativa*) from plant analysis. Agron. J. 57:364-366.

Putman, H. D. and E. L. Schmidt. 1959. Studies on the free amino acid fraction of soils. Soil Sci. 87:22-27.

Roe, D. A., P. S. Miller, and L. Lutwak. 1966. Estimation of sulfur in biological materials by atomic absorption spectrometry. Anal. Biochem. 15:313-322.

Sanford, J. O. and J. D. Lancaster. 1962. Biological and chemical evaluation of the readily available sulfur status of Mississippi soils. Soil Sci. Soc. Amer. Proc. 26:63-65.

Shorey, E. C. 1913. Some organic soils constituents. US Dep. Agr. Bur. Soils Bull. 88.

Sowden, F. J. 1955. Estimation of amino acids in soil hydrolysates by the Moore and Stein methods. Soil Sci. 80:181-188.

Sowden, F. J. 1956. Distribution of amino acids in selected horizons of soil profiles. Soil Sci. 82:491-496.

Sowden, F. J. 1958. The forms of nitrogen in the organic matter of different horizons of soil profiles. Can. J. Soil Sci. 38:147-154.

Spencer, K. 1959. Growth and chemical composition of white clover as affected by sulfur supply. Australian J. Agr. Res. 10:500-509.

Spencer, K. and J. R. Freney. 1960. A comparison of several procedures for estimating the sulfur status of soils. Australian J. Agr. Res. 11:948-959.

Steel, R. D. G. and J. H. Torrie. 1960. Principles and procedures of statistics. McGraw-Hill Book Co., New York.

Steinbergs, A. 1955. A method for the determination of total sulphur in soils. The Anal. 80:457-461.

Stevenson, F. J. 1956. Isolation and identification of some amino compounds in soils. Soil Sci. Soc. Amer. Proc. 20:201-204.

Stewart, B. A. and C. J. Whitfield. 1965. Effects of crop residue, soil temperature and sulfur on the growth of winter wheat. Soil Sci. Soc. Amer. Proc. 29:752-755.

Tabatabai, M. A. and J. M. Bremner. 1970. Arylsulfatase activity of soils. Soil Sci. Soc. Amer. Proc. 34:225-229.

Tabatabai, M. A. and J. M. Bremner. 1972a. Distribution of total and available sulfur in selected soils and soil profiles. Agron. J. 64:40-44.

Tabatabai, M. A. and J. M. Bremner. 1972b. Sulphur in Iowa soils. Sulphur Inst. J. 8:10-13.

Thomas, M. D., R. H. Hendricks, and G. R. Hill. 1950. Sulfur content of vegetation. Soil Sci. 70:9-18.

Toth, S. J., A. L. Prince, A. Wallace, and D. S. Mikkelsen. 1948. Rapid quantitative determination of eight mineral elements in plant tissue by a systematic procedure involving a flame photometer. Soil Sci. 66:459-466.

Ulrich, A. and F. J. Hills. 1967. Principles and practices of plant analysis, p. 11-20. *In* M. Stelley (ed.) Soil testing and plant analysis, Part II. Soil Sci. Soc. Amer., Inc., Madison, Wis.

Walker, D. R. and C. F. Bentley. 1961. Sulfur fractions of legumes as indicators of sulfur deficiency. Can. J. Soil Sci. 41:164-168.

Whitehead, D. C. 1964. Soil and plant nutrition aspects of the sulphur cycle. Soils Fert. 27:1-8.

Widdowson, J. P. 1970. Available sulphur in some Iowa soils. Ph.D. Dissertation. Iowa State University, Ames, Iowa.

Wilcox, G. E. and J. E. Sedberry, Jr. 1954. The effects of additions of lime, sulfur and minor elements on cotton grown on Shubuta fine sandy loam, p. 22-29. *In* Annual progress report, North Louisiana Hill Farm Exp. Sta. La. State Univ. Agr. Exp. Sta.

Williams, C. H. 1967. Nitrogen, sulphur and phosphorus, their interactions and availability. Int. Soc. Soil Sci. Trans. Comm. II, IV. 93-111.

Williams, C. H. and A. Steinbergs. 1964. The evaluation of plant available sulfur in soils: II. Plant Soil. 21:50-62.

Williams, C. H., E. G. Williams, and N. M. Scott. 1960. Carbon, nitrogen, sulfur and phosphorus in some Scottish soils. J. Soil Sci. 11:334-346.

Woodward, J. 1922. Sulfur as a factor in soil fertility. Bot. Gaz. 73:81-190.